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Morphological processing in Chinese engages left temporal regions

Ka I Ip[a,1], **Rebecca A. Marks**[a,1], **Lucy Shih-Ju Hsu**[c], **Nikita Desai**[a], **Ji Ling Kuan**[a], **Twila Tardif**[a], **Ioulia Kovelman**[a,b,*]

[a]Department of Psychology, University of Michigan, 530 Church Street, Ann Arbor, MI 48109, United States

[b]Center for Human Growth and Development, University of Michigan, 300 North Ingalls, Ann Arbor, MI 48109, United States

[c]Department of Psychology, The University of Hong Kong, Pokfulam, Hong Kong

Abstract

Morphological awareness, the ability to manipulate the smallest units of meaning, is critical for Chinese literacy. This is because Chinese characters typically reflect the morphemic, or morpho-syllabic units of language. Yet, the neurocognitive mechanisms underlying Chinese speakers' morphological processing remain understudied. Proficient readers (N = 14) completed morphological and phonological judgment tasks in Chinese, in both auditory and visual modalities, during fMRI imaging. Key to our inquiry were patterns of activation in left temporal regions, especially the superior temporal gyrus, which is critical for phonological processing and reading success. The findings revealed that morphological tasks elicited robust activation in superior and middle temporal regions commonly associated with automated phonological and lexico-semantic analyses. In contrast, the rhyme judgment task elicited greater activation in left frontal lobe regions, reflecting the analytical complexity of sound-to-print mapping in Chinese. The findings suggest that left temporal regions are sensitive to salient morpho-syllabic characteristics of a given language.

Keywords

Literacy; Cross-linguistic; Morphological awareness; Phonological awareness; fMRI

1. Introduction

Neurobiological models of literacy emphasize the critical role of left posterior temporal regions in linking speech and print for proficient reading (Hickok & Poeppel, 2007; Pugh et al., 2001). These include the left posterior superior temporal region (STG), which is thought

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[*] Corresponding author at: Department of Psychology, University of Michigan, 530 Church Street, Ann Arbor, MI, 48109, United States. Kovelman@umich.edu (I. Kovelman).

[1] These authors have equal contribution.

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to support phonological processing and the left posterior middle temporal region (MTG), which is thought to support lexical and semantic analyses for word-level processes (Friederici & Singer, 2015; Hickok & Poeppel, 2007). Studies of *phonological awareness* (the ability to actively manipulate units of sound) have provided a strong link between left STG functioning and proficient literacy in speakers of Indo-European languages with alphabetic scripts (Pugh et al., 2013; Raschle, Zuk, & Gaab, 2012). Yet, the role of posterior temporal regions in Chinese literacy is less clear, as Chinese characters transmit morphemic information with greater predictability than phonemic information (Brennan, Cao, Pedroarena-Leal, McNorgan, & Booth, 2013; Cao, Brennan, & Booth, 2015; Siok, Niu, Jin, Perfetti, & Tan, 2008). The main goal of our study was to investigate the role of left posterior temporal regions in processing the meaning and sound of Chinese morphemes, the language units that map most reliably onto Chinese characters. By uncovering the neurocognitive basis of morphological structure awareness in Chinese, we aim to shed light on the source of cross-linguistic differences in reading between Chinese and Indo-Eur-opean languages such as English (Perfetti, Cao, & Booth, 2013).

Both phonological awareness (the ability to manipulate units of sound), and morphological awareness (the ability to manipulate units of meaning) are essential for successful reading acquisition. The sound-to-letter mapping principle of alphabetic languages has made phonology a common target for studying the relationship between language and literacy. Nevertheless, recent discoveries point to the importance of morphological awareness for reading acquisition across languages (e.g., Colé et al., 2018; Desrochers, Manolitsis, Gaudreau, & Georgiou, 2018; Ruan, Georgiou, Song, Li, & Shu, 2018). For instance, in a longitudinal study of English speaking children, both phonological and morpholo-gical awareness made unique contributions to reading outcomes, though the strength of each predictor varied across ages (Deacon & Kirby, 2004).

Importantly, the relative contribution of phonological and morphological abilities to literacy also vary across languages. In a cross-linguistic study of 2nd graders, McBride-Chang et al. (2005) discovered that phonological awareness was the strongest predictor of word reading in English above other metalinguistic skills. In contrast, morphological awareness was the strongest predictor of word reading in Chinese, while phonological awareness made a smaller contribution relative to English (McBride-Chang et al., 2005).

Morphological processing is of particular importance to Chinese literacy acquisition because Chinese characters map directly onto morpho-syllabic units. The majority of commonly used Chinese words (95%) are compounds composed of two or more morphemes, each represented by a character (Zhang, 2011). For instance, in Chinese, the word "火车" (*huo3che1 = train*) is a morphologically complex compound with two syllables (i.e., "火" (*huo3* = fire) + "车"(*che1* = car)) that are also meaningful root morphemes (Liu et al., 2010). These roots can be combined with other morphemes to make new compounds. For instance, if the morpheme "火" (*huo3* = fire) is combined with another morpheme「山」(*shan1*) "mountain", it becomes "火山" (*huo3shan1* = fire-mountain = volcano) or if combined with "机" "machine" to (*ji1* = machine), it becomes "火机" (*huo3ji1* = fire-machine = lighter). More importantly, Chinese words' morphological composition is rule-governed, and of particular importance is the order in which morphemes can be arranged. In the examples above, "*fire*" modifies the morpheme “山” (*shan1* =mountain) “mountain” to form the compound word “火山” (*huo3shan1* = volcano). When this morphological structure is modified by changing the order of the morphemes, the word acquires a different meaning (i.e., “山火” (*shan1huo3*) means mountain fire). In other cases, changing the word order could result in a meaningless compound (e.g., “机火” (*ji1huo3*) is not a type of machine or fire), highlighting the critical role of morphological structure in lexical processing and visual recognition.

Morphological processing and knowledge of the underlying morphological structure of words is thus critical for successful reading acquisition in Chinese. However, although prior research has explored the brain basis of phonological and morphosyntactic processing in Chinese, the neural basis of processing morphological *structure* in Chinese remains unknown. Examining the neural mechanisms involved in both phonological and morphological processing in Chinese, across both the auditory and visual modalities, will help to further illuminate both language-specific and universal components of word processing across languages.

1.1. Brain basis of phonological and morphological awareness in Chinese

1.1.1. Phonological awareness in the visual modality—Studies of phonological awareness processing in the visual modality have found robust activations along the phonological neural pathways, including the dorsal aspect of left inferior frontal gyrus (IFG; BA44/9), left STG, and inferior parietal regions (Cao et al., 2010; Liu et al., 2009). Cross-linguistic comparisons suggest stronger left frontal and weaker temporal-parietal activation in Chinese relative to English readers (Cao et al., 2015; Siok et al., 2008; Tan, Laird, Li, & Fox, 2005). For example, when asked to read two words and decide if they rhyme, typical English readers showed significant activation in left IFG and temporal-parietal regions (Temple et al., 2003). In contrast, Chinese readers recruited left inferior and middle frontal (MFG) regions but did not significantly activate temporal regions when performing a similar task relative to a control tone judgment task (Siok et al., 2008). Chinese characters are known to have a lower sound-to-print predictability than English alphabetic words and so the patterns of increased left frontal but reduced temporal activation is typically interpreted to suggest the necessity of engaging complex linguistic (IFG) and working memory (MFG) processes when extracting phonological information from Chinese charsacters (Siok et al., 2008; Tan et al., 2005).

1.1.2. Phonological awareness in the auditory modality—Research also finds robust left IFG activation during phonological awareness tasks in Chinese in the auditory modality (Brennan et al., 2013; Cao et al., 2015; Liu et al., 2009). A developmental, cross-linguistic comparison of children and adults finds that English but not Chinese speakers showed a developmental increase in activation in the left temporal STG/MTG and inferior parietal (IPL) region during rhyme judgment tasks in the auditory modality (Brennan et al., 2013). These findings have been taken to suggest language-specific adaptations in the left temporal region’s functionality to support literacy acquisition, adaptations that might be different across English and Chinese.

1.1.3. Morphological awareness in the visual modality—

Morphological processing across languages is tightly linked with both phonological and semantic analyses because morphemes are the smallest meaningful units of sound. Across languages and modalities, making a semantic decision, such as deciding if a word is a real word or a pseudoword (*bucket* vs. *blicket),* is a living being (*car vs. cat*) or if two words are related (*pillow-bed*), engages the semantic neural system that includes the ventral IFG (BA 45/47) and MTG (Booth et al., 2006; Chee, Tan, & Thiel, 1999; Liu et al., 2009). Prior studies of morphological processing have used lexical decision tasks such as these to examine the brain basis of lexical morphology (Liu et al., 2013; Zou, Packard, Xia, Liu, & Shu, 2015). For instance, a visual study of morphological processing in Chinese by Liu et al. (2013) asked participants to complete a semantic relatedness task that included word pairs that were either congruent or incongruent. Congruent pairs shared a word component (a morpheme) with the same sound and meaning (akin to *classroom-bedroom*), whereas incongruent pairs shared a component with the same sound, but not the same meaning (akin to *classroom-mushroom*). The study discovered that only typically-developing readers showed stronger activation for incongruent pairs in left frontal (BA 9 & 47) regions. In contrast, children with dyslexia did not show this effect, corroborating theoretical perspectives and behavioral findings that dyslexia in Chinese is associated with reduced sensitivity to morphological composition (McBride-Chang et al., 2005).

Morphological awareness in the auditory modality has been explored using a similar paradigm as Liu et al. (2013), described above. For instance, Zou et al. (2015) found significant activations in left IFG, MFG, and fusiform gyrus, as well as bilateral STG regions during Chinese morphological judgments. These findings were taken to suggest that Chinese morphological processing, especially in the auditory modality, is tightly linked with both semantic and phonological processing. This is consistent with the notion that Chinese syllables are morphemes, and therefore include lexical and phonological components, as compared to syllables in Indo-European languages which can often be meaningless in and of themselves.

While the prior studies address the question of lexical morphological processing by asking participants to decide if words like 唱歌 “sing a song” – 民歌 “folk song” vs 礼物 “gift” – 生物 “living things” are semantically related, these do not address the critical issue of Chinese words’ morphemic *structure*. The ordering of the morphemic units within a word is a critical component of Chinese word formation and processing thought to underlie successful vocabulary acquisition and subsequent reading acquisition in Chinese (McBride-Chang et al., 2005). Understanding the neural bases of Chinese speakers’ sensitivity to morphological structure informs our understanding of how language-specific experiences influence the functionality of left perisylvian regions, especially left inferior frontal and temporal regions, considered to be critical for learning to read across languages and for dis-criminating between fluent vs. dyslexic readers (Pugh et al., 2001).

1.2. The current study

The study’s two primary objectives were to understand the neuro-cognitive basis of morphological structure awareness in Chinese as well as to shed light on the source of cross-linguistic differences in reading between Chinese and Indo-European languages such as English. In particular, there is currently a paradox in the field in how we under-stand Chinese literacy in relation to other orthographies. On the one hand, Chinese characters map onto morphemes. Logically, Chinese speakers' ability to construct novel morphological items precedes and predicts reading ability and dyslexia in Chinese (McBride-Chang, Shu, Zhou, Wat, & Wagner, 2003). On the other hand, the neuroimaging work on literacy and dyslexia in Chinese has predominantly been in-formed by rhyme judgment tasks that are more characteristic of Indo-European languages. This neuroimaging work with rhyme judgment tasks has yielded cross-linguistic differences in left temporal regions, which are essential for segmenting the linguistic stream into morpho-phonological constituents (Cao et al., 2015; Siok et al., 2008). We have therefore hypothesized that tasks that tap into morphological segmentation in Chinese would effectively engage the left temporal regions. To test this hypothesis, we designed experimental tasks that were maximally matched to morphology tasks previously used to predict literacy in Chinese as well as prior neuroimaging rhyme tasks previously used to examine cross-linguistic differences in reading between English and Chinese.

Behavioral studies and clinical assessments aimed at identifying literacy success vs. dyslexia in Chinese typically use morphological structure awareness tasks that require children and adults to make *novel compound* words, following an example of an existing compound word. For instance, children are often asked "If a tree that grows apples is called an "apple-tree" (ping2guo3shu4), what would a tree that grows bread be called?" (The correct answer would be a "bread tree" (mian4bao1shu4) and not "tree bread" (shu4 mian4bao1).) These behavioral tasks uniquely predict Chinese single-word recognition above the contributions of other critical literacy skills, including vocabulary knowledge, rapid naming, and phonological awareness (McBride-Chang et al., 2003). Therefore, we designed a neuroimaging measure of morphological structure awareness in Chinese that maximally resembled such behavioral tasks, but involved a decision in lieu of overt articulation to avoid motion artifacts associated with articulation during neuroimaging. Native adult speakers/readers of Chinese were presented with two words and asked to judge if the second word, the new compound, was acceptable or not. Acceptable new words conformed to the compounding rules of Chinese, whereas unacceptable items violated those rules (see Methods & Appendix for more details).

During fMRI neuroimaging, adult native speakers/readers of Chinese completed the morphological structure judgment task as well as a traditional phonological rhyme judgment task, and a verbal word match control condition. Participants completed tasks in auditory and visual modalities separately, to tap into morphological and phonological processing in both speech and print. Because spoken morphemes map onto individual characters, we explored the possibility that there may be a greater similarity between spoken morphology and print in Chinese than spoken phonology and print, especially in the left temporal brain regions. Our primary prediction was that morphological processing would engage the left inferior frontal (IFG) and posterior temporal (MTG/STG) regions essential to lexico-semantic and phonological processing of morphological structure (Friederici & Singer, 2015; Hickok & Poeppel, 2007). The overarching goal was to illuminate the neurocognitive mechanisms underlying Chinese morphological and phonological processing, to better inform our understanding of the language-specific as well as universal components of successful reading acquisition.

2. Materials and methods

2.1. Participants

Fifteen right-handed, neurotypical adult native speakers of Mandarin Chinese (7 females; mean age = 23.60 years; standard deviation [SD] = 2.92; age range = 19–28) participated in the study. All participants were international students from mainland China studying in the United States for a bachelor's or master's degree and had lived in the US for 2–5 years at the time of testing. They completed a background screening questionnaire in which they reported being highly proficient in Chinese without a history of language, literacy, or hearing impairments. Participants also completed behavioral measures (detailed below) that confirmed the normative levels of participants' Chinese proficiency and working memory (as measured with digit span). All participants reported having moderate to high levels of English speaking, reading and writing fluency. One participant was excluded due to technical issues during T1 image acquisition. Of the remaining fourteen participants, two individuals each failed to complete one experimental task (auditory rhyming and auditory morphology, respectively). Therefore, subsequent analyses were conducted using either thirteen or fourteen subjects.

2.2. Behavioral measures

All participants completed published experimental measures of lit-eracy, language and cognitive abilities in Mandarin Chinese. These included:

2.2.1. Morphological awareness—Participants completed a Morphological Construction task, previously used by McBride-Chang et al. (2003). Participants were required to combine known morphemes in new ways ("If a ball made from snow is called "snowball" */xue3qiu2/*, what would a ball made from mud be called?" The correct answer would be "mudball" */ni2qiu2/*).

2.2.2. Phonological awareness—Participants completed the Chinese phoneme deletion task (Newman, Tardif, Huang, & Shu, 2011), adapted from the elision subtest of the Comprehensive Test of Phonological Processing (CTOPP). Participants were asked to pronounce a word while omitting a phonetic unit, starting with syllables and then moving to smaller phonetic units with greater complexity and different positioning within the word (e.g., "*xi1gua1*", meaning watermelon, without "xi1" would be "*gua1*").

2.2.3. Reading fluency—The reading fluency task was modeled after a previous study (Lei et al., 2011) in which participants were asked to read as many sentences as possible within 3 min while indicating if the sentence was semantically correct or incorrect. Scores from this task were used as an indication of the participants' level of proficiency in Mandarin. Higher scores indicated better performance.

2.2.4. Digit span—

Participants completed the forward and backward digit span task from the Chinese Wechsler Adult Intelligence Scale–Revised in China (WAIS-RC; Gong, 1992). Forward digit span measures attention and concentration. Participants were asked to orally repeat digit sequences of increasing length in the same order that the experimenter presented them. Backward digit span measures short-term working memory. Participants were asked to orally repeat digit sequences of increasing length in the reverse order that the experimenter presented them. This task was scored by the number of digits correctly repeated in the for-ward and backward sequence. Higher scores indicated better performance.

2.3. fMRI tasks

During neuroimaging, participants completed tasks of morphological structure and phonological judgment in both the auditory and visual modalities. During the auditory trials, participants heard two words, and during the visual trials, participants saw two words. Within each run, experimental pairs from each task (i.e., auditory morphology) were presented in a blocked design, interspersed with blocks of a verbal control task and a perceptual control task. Details of the morphological, phonological, and verbal control tasks are presented below; the perceptual control task was not analyzed for this study, and will not be discussed. Because all participants were native Mandarin speakers from mainland China, all visual stimuli used simplified Chinese characters and all auditory stimuli were spoken in Mandarin Chinese.

2.3.1. Morphological judgment task—

Participants completed a Chinese compound morphology task which was modeled after the Chinese Morphological Construction task previously shown to predict reading acquisition in Chinese (McBride-Chang et al., 2003). During this task, participants heard or saw two words consecutively. The first compound word was a real word [e.g., “病人” (*bing4ren2* = sick-man) or “雪人” (*xue3ren2* = snow-man)]; while the second word was a new pseudoword that resembled the first real word and either conformed to [e.g., “病花” (*bing4hua1* = sick-flower)] or violated [e.g., “猫雪” (*mao1xue3* = cat-snow)] the structural constraints of morphological compounding in Mandarin. Participants were instructed to indicate as quickly and as accurately as possible via button press, whether the new pseudoword was “good” or “bad” (i.e. whether it confirmed or violated morphological constraints). Acceptable new compound words (see Appendix) involved substitutions to one of the morphemes/syllables that can occur in any word order (1st, 2nd, or 3rd) but did *not* involve changes in the morphological structure of the compound word. For example, the novel compound “洗鞋机” (*xi3xie2ji1* = wash + shoes + machine = washing machine for shoes) + machine = washing machine for shoes” (from an existing word 洗衣机 */xi3yi1ji1/* “wash + *clothes* + machine = washing machine for clothes) is acceptable, because the 2nd syllable/character “鞋” (*xie2* = shoes) becomes the modifier of the morpheme “机” (*ji1*) to represent a machine for shoes. This item maintains the order of Chinese morphosyllabic units and thus does not change the morphological structure. This is essential because the morphological structure of compound words in Chinese is governed by strict rules.

Unacceptable new compound words intentionally modified the order of syllables/characters. When the order of the morphosyllabic units violates the expected word structure, then the part of speech and what is being modified may change, or the “head” noun may change, resulting in a meaningless compound. For instance, if the morphological structure of the new compound “洗鞋机” (*xi3xie2ji1* = wash + shoes + machine) is modified by changing the order of the morphemes to “鞋机洗” (*xie2ji1xi3* = shoes + machine + wash), the word acquires a different meaning (*xie2ji1xi3* = shoes machine being washed) or if it is modified to “洗机鞋” (*xi3ji1xie2* = ‘wash + machine + shoes) it results in meaningless compound (e.g., *xi3ji1xie2* is not a type of machine and has no meaning). Therefore, participants had to pay close attention to all of the morphosyllabic units to determine whether the word pair was acceptable or not. This task requires individuals to be sensitive to the morphological structures of Chinese compound words, and should thus tap into the neural circuitry essential for morphological structure processing.

The words in this task had an average of 2.6 ± 0.5 syllables, 7.2 ± 1.6 phonemes, 2.6 ± 0.5 characters, and 20.99 ± 6.3 strokes. To verify the ecological validity of this task for Chinese literacy acquisition, this task was first used with 56 Chinese-speaking children. The new morphological compound judgment task effectively predicted children’s literacy, explaining more variance than phonological awareness, as is typical of Chinese literacy in early grades (total R-square = 0.48, R-square for morphological task 0.31; Hsu, Ip, Arredondo, Tardif, & Kovelman, 2016; Ip, Hsu, Arredondo, Tardif, & Kovelman, 2016).

2.3.2. Phonological (rhyme) judgment task—Participants completed a rhyme judgment task during which they either heard (auditory modality version) or saw (visual modality version) two words consecutively and were instructed to respond as quickly and as accurately as possible with a button press indicating whether the two words rhymed or not based on the last character (e.g., “银行 /*yin2hang2*/” – “新郎 /*xin1lang2*/” = rhyme; “打鼓 /*da3gu3*/” – “头发 /*tou2fa4*/” = do not rhyme; Liu et al., 2009). While the rhyming word pairs shared a phonetic component, none of the pairs included words with identical 2nd syllables/characters, ensuring that rhyming words did not have shared morphemes. The words in the rhyme judgment task had an average of 2.0 ± 0 syllables, 5.9 ± 0.8 phonemes, 2.0 ± 0 characters, and 17.7 ± 4.2 strokes.

2.3.3. Verbal control word-match—Each experimental task included blocks of a verbal control task, participants either heard or saw two words, consecutively, and decided if the words were the same or different (e.g. “家乡” (*jia1xiang1*) – “家乡” (*jia1xiang1*) = same; “海盗” (*hai3dao4*) – “地球” (*di4qiu2*) = different). Like the non-matching pairs in the rhyming task, there were no identical characters/syllables in the non-matching pairs of the control task. This control task required participants to make a judgment about two words but did not require any additional computations about the words’ morphemic or phonemic units.

We created two versions of the verbal control task, one to match the morphological structure awareness stimuli and one to match the phonological awareness stimuli. This was done because the morphological task words were significantly longer than the phonological awareness words. The control task that matched the morphological stimuli included words with an average of 2.6 ± 0.5 syllables, 7.4 ± 1.9 phonemes, 2.6 ± 0.5 characters, and 20.2

± 6.6 strokes. The control task that matched the phonological stimuli included words with an average of 2.0 ± 0 syllables, 5.6 ± 0.8 phonemes, 2.0 ± 0 characters, and 16.8 ± 4.3 strokes. No significant difference was found between experimental versus control tasks on the numbers of syllables, phonemes, characters, or strokes.

2.4. Procedure

Before neuroimaging, participants completed practice trials of the experimental measures with words that differed from in-scanner word stimuli. Participants were taught to respond to word pairs as quickly and as accurately as possible with a button press. After task training, participants completed four experimental runs: visual morphology, auditory morphology, visual phonology, and auditory phonology. The order of runs was randomized across participants.

Each run included 5 blocks of the experimental condition and 5 blocks of the verbal control condition in the same modality. For example, the visual morphology run included blocks of visual morphology and blocks of visual verbal control. Different items were used for visual and auditory trials, but the items were all linguistically similar and matched for the number of phonemes, syllables, and characters. The order of the blocks was randomized within each run and counter-balanced across participants. Preceding each block, participants received 2 s of instructions informing them of the task they were about to complete (e.g., “rhyme judgment now”). All visual tasks had white text centered on a black screen, while all auditory tasks had white fixation centered on a black screen. Visual cues for different tasks (e.g., “rhyme judgment”) were indicated with different color backgrounds.

2.5. fMRI data acquisition and analyses

2.5.1. fMRI data acquisition & processing—All fMRI images were collected on a 3-T GE MR750 scanner with an 8HRBRAIN head coil (General Electric, Milwaukee, WI). Functional T2*images were then acquired using a reverse spiral sequence (43 mm slices, 64 × 64 resolution, TR = 2000 ms, TE = 30 ms, FA = 90°, FOV = 22 cm). Anatomical images were acquired using a 3D BRAVO Sequence echo image (TR = 12.2 ms, TE = 5.2 ms, TI = 500 ms, FA = 15°, FOV = 26 cm, 1.2 mm slice thickness, 124 axial slices).

We used SPM12 (Wellcome Department of Cognitive Neurology, London, UK), implemented in Matlab R2016b (MathWorks Inc, Sherborn, MA) for standard pre-processing and statistical analyses. Pre-processing included slice timing correction, realignment, co-registra-tion of the anatomical to the functional images, normalization of the images to the SPM template in MNI space, and smoothing with a 6 mm FWHM Gaussian kernel (see Weng, Xiao, & Xie, 2011 for further details). Six motion parameters were included as regressors in the individual level GLMs. We found only minimal head movements for all participants, therefore no participant was excluded due to head motion. Each subject’s data were high-pass filtered at 128 s.

2.5.2. Whole brain analysis—Each subject’s data was analyzed using a fixed-effects model that included the experimental task (either morphology or phonology) and the control task as the two factors. Because all of our experiment tasks used a block design, yes/no responses trials were averaged within the block. Because accuracy was near ceiling, we did not anticipate accuracy effects on either yes or no answers. For each participant, the BOLD impulse response was modeled using a dual-gamma canonical hemo-dynamic response function. Contrast images were generated for each task/run, including experimental > verbal control and experimental > resting baseline contrasts. Second-level analyses were performed to obtain group-level contrast images, which were then examined using one-sample *t*-tests for whole-brain activations at an FDR cluster-corrected threshold of $p < 0.001$ and an extent threshold (ET) of 205 voxels, as recommended by 3dClustSim (Cox, Chen, Glen, Reynolds, & Taylor, 2017).

2.5.3. Paired t-tests—To identify brain regions specifically related to morphology relative to phonology, we used paired *t*-tests to examine whole-brain differences between auditory phonology vs. auditory morphology, as well as visual phonology vs. visual morphology (effect of the experimental task). To identify brain regions more specifically related to the auditory relative to the visual modality, we used paired *t*-tests to further compare au-ditory vs. visual phonology, as well as auditory vs. visual morphology (effect of modality). All contrasts were thresholded at $p < 0.001$ with an extant threshold (ET) of > 205 voxels, as recommended by 3dClustSim (Cox et al., 2017).

2.5.4. ROI identification & analyses—The study aimed to identify brain regions that were common versus specific to phonological and morphological processing in Chinese. To identify regions of interest, we first conducted a conjunction analysis to identify common regions of activation across all four experimental conditions (auditory phonology, auditory morphology, visual phonology, and visual morphology). We selected task > verbal control contrast images, which were the most conservative in terms of revealing the brain activations for morphological and phonological awareness over and above typical lexical processing requirements, and used a liberal exploratory threshold of $p < 0.05$, uncorrected. This analysis revealed common clusters in the left IFG/MFG, left MTG/STG, and left inferior parietal region (see Fig. 3). These common regions aligned with our a priori hypotheses, which included left frontal (IFG/MFG) and tempo-parietal (STG/MTG) regions, which showed significant activation during prior morphological awareness tasks in Chinese (Liu et al., 2013; Zou et al., 2015)

2.5.5. ROI extraction—We used AFNI (Cox, 1996) to create 8-mm spheres centered around the center of mass of the three clusters that emerged from the con-junction analysis. We extracted these regions' mean *t*-statistic from the experimental conditions > verbal control contrasts for each task in each modality using 3dROIstats. Activity within each region of interest was probed further with planned contrasts to uncover subtle task- and modality-related differences.

3. Results

3.1. Behavioral performance

3.1.1. Chinese language and literacy skill—Participants performed at ceiling on all Chinese language and literacy tasks, confirming their adult-like proficiency in Chinese despite attending college in the United States. We did not pursue further analysis with these measures.

3.1.2. In-scanner task accuracy—A three-way (2 × 2 × 2) repeated measures ANOVA for the two modalities (auditory vs. visual), two conditions (experimental vs. word matching condition) and two tasks (morphological vs. phonological judgment) was conducted to examine participants' in-scanner task accuracy. There was a significant main effect of modality, $F(1, 13) = 11.85$, $p = .004$. Post hoc comparisons with Bonferroni adjustment revealed that participants performed more accurately on tasks in the visual than the auditory modalities. There was no main effect of condition: participants performed slightly more accurately on the control than the experimental conditions, but this effect was marginal, $F(1, 13) = 4.08$, $p = .064$. There was no main effect of task, $F(1, = 2.31$, $p = .16$, nor interaction between tasks or modalities (Table 1).

3.1.3. In-scanner tasks reaction time—A similar 3-way repeated measures ANOVA for participants' reaction time revealed that participants responded significantly faster in the visual than the auditory modality, $F(1, 13) = 200.22$, $p < .001$. There was a significant main effect of condition, $F(1, 13) = 111.78$, $p < .001$, indicating that participants were faster during the control than the experimental conditions. There was also a significant main effect of task, $F(1, 13) = 39.73$, $p < .001$, indicating that participants were faster during the morphological than the phonological awareness tasks. Furthermore, there was a significant interaction between modality and task, $F(1, 13) = 15.83$, $p = .002$. As can be seen in Table 1, the participants performed faster during auditory morphological awareness than the auditory phonological awareness tasks.

3.2. fMRI main effects of conditions

3.2.1. Brain bases of morphological structure awareness—The first step in our analyses was to investigate the brain bases of morphological awareness relative to the control condition. As seen in Fig. 1, *t*-test comparisons for the morphological awareness minus the verbal control contrasts revealed greater left IFG activation extending into the MFG and left MTG/STG during both auditory and visual conditions. The auditory morphology minus control contrast also revealed greater right MTG/STG, while the visual morphology minus control revealed bilateral occipital activation (see Table 2 for the coordinate listings).

3.2.2. Brain bases of phonological awareness—As can be seen in Fig. 1, *t*-test comparisons for the auditory phonological awareness minus control contrast revealed greater activations in bilateral STG/MTG. The visual phonology minus control contrast revealed greater activations in the left IFG and MFG, as well as bilateral occipital-temporal regions (see Table 2).

3.2.3. Brain bases of morphological versus phonological processing—In order to directly identify brain regions more specifically related to morphology relative to phonology, we compared the two conditions using two paired *t*-tests (auditory morphology vs. phonology and visual morphology vs. phonology) using task > verbal control contrast images. Neither analysis revealed any significant effect of the experimental task at the whole-brain level. Task differences were probed further in a priori regions of interest identified through the conjunction analyses detailed below.

3.2.4. Brain bases of auditory versus visual processing—To identify brain regions more specifically related to auditory relative to visual processing, we used paired *t*-test to further compare auditory vs. visual phonology, as well as auditory vs. visual morphology. These analyses used task > verbal control contrast images with a cluster threshold of 205 voxels at uncorrected $p < 0.001$ as recommended by 3dClustSim (Cox et al., 2017).

Both analyses revealed an effect of modality in bilateral STG and occipital regions for the task minus resting baseline comparison (see Fig. 2). Additionally, the comparison between auditory and visual phonology revealed greater activation in left superior parietal lobule ($x = -28$, $y = -68$, $z = 32$, k = 219, $T = 6.00$) and right middle frontal gyrus extending into the precentral gyrus ($x = 32$, $y = -14$, $z = 70$, k = 287, $T = 7.55$) during the visual rhyming task.

3.3. ROI analysis

3.3.1. Conjunction analyses—Conjunction analysis using task > verbal control contrasts at an exploratory uncorrected threshold of $p < .05$ revealed three left-lateralized ROIs that were common to all conditions: left IFG/MFG (BA 44/45; 2006 voxels), left MTG/pSTG (BA 21; 403 voxels), and left precuneus inferior parietal lobule extending into the cuneus (BA 7; 120 voxels). We extracted 8 mm spheres around the center of mass of each common region. The mean *t*-statistic for these regions across experimental conditions is plotted in Fig. 3. We then compared the mean *t*-statistic in each region of interest across conditions. Results of these ROI comparisons revealed that the MTG/pSTG region was more active during the morphology task than during the phonology task across both modalities.

3.3.2. Temporal conjunction region—A paired *t*-test comparison revealed greater left MTG/pSTG activation during the auditory morphology task than the auditory phonology task ($t(11) = 3.62$, $p = .004$). As can be seen in Fig. 3, this effect generalizes across modalities but is not statistically significant in the visual morphology versus visual phonology condition ($t(13) = 2.07$, $p = .059$). This result is of particular interest, as previous studies have suggested that the superior/middle temporal region may be particularly sensitive to cross-linguistic experiences, given a developmental increase during a phonology task for English speakers but not Chinese speakers (Brennan et al., 2013). Here, we suggest that the MTG/pSTG is more heavily recruited for *morphological processing* than phonological processing among Chinese speakers, a logical outcome given the relatively greater importance of morphology than phonology for Chinese reading acquisition. Additionally, the temporal region was recruited more heavily for the two auditory tasks than the two visual tasks ($t(12) = 3.05$, $p = .011$).

3.3.3. Frontal conjunction region—Paired t-tests revealed no significant differences in activation in the shared frontal region across the four experimental tasks. The IFG appeared to be slightly more active during the two visual tasks than the auditory tasks, though this result reached only marginal significance ($t(11) = 2.19$, $p = .051$). There were no significant differences between morphological and phonological processing.

3.3.4. Parietal conjunction region—While the inferior parietal region appeared to be slightly more active during both the auditory and visual morphology tasks than phonology tasks, this difference was not significant ($t(11) = 1.47$, $p = .169$).

4. Discussion

To understand the language-specific influence of learning to read in Chinese on the functionality of the reading brain, we investigated the brain bases of morphological structure awareness in Chinese. We predicted that morphological structure awareness, a measure of Chinese speakers' sensitivity to the salient morpho-phonological characteristics of their language (McBride-Chang et al., 2005), would elicit robust activation in left inferior frontal as well as posterior temporal regions classically associated with fluent literacy across languages (Rueckl et al., 2015). Consistent with our predictions, we found that our morphological structure task elicited activation in left posterior temporal MTG/STG regions across both auditory and visual modalities, relative to the verbal control condition. Furthermore, ROI analyses revealed that the left superior temporal activation was stronger for morphological than phonological processing in Chinese. These results shed new light on the functionality of left temporal regions for language and literacy. In particular, the STG is considered critical for learning to read in alphabetic languages and is often associated with phonological sound-to-letter mapping processes (Temple et al., 2003). Yet, in Chinese, a language with opaque sound-to-print mappings, the role of left temporal regions has been less clearly defined (Siok et al., 2008). Our findings reveal robust engagement of left temporal regions, including left STG, during morphological tasks critical to Chinese literacy, and suggest that the functionality of these temporal regions supports readers' sensitivity to the core morpho-phonological characteristics of their language.

Our study offers three primary findings. First, we uncovered a network of regions engaged in processing morphological structure in Chinese. In the present study, we were specifically interested in the speaker's sensitivity to word structure and therefore used novel lexical forms that either conformed to or violated compounding rules in Chinese. This method is notably distinct from previous neuroimaging studies of morphological processing, in which lexical morphology is often used to help disambiguate the relative contribution of decomposable or structural aspects of the word processing versus whole-word semantic recognition (for review of neuroimaging work on morphology see Leminen, Smolka, Duñabeitia, & Pliatsikas, 2018). Our morphological structure task revealed brain activation which extended through regions typically associated with the "dorsal" network of language processing, such as dorsal IFG and posterior STG (Hickok & Poeppel, 2007), as well as the network of lexico-semantic processing, such as ventral IFG and posterior MTG (Fig. 1). These findings are generally consistent with the theoretical model that no specific brain region is selectively responsible for morphological processing. Rather, morphological processing is accomplished through the broadly distributed network of mechanisms for analyzing word sound, meaning, and structure (Arredondo, Ip, Shih Ju Hsu, Tardif, & Kovelman, 2016; Cavalli et al., 2016). The activation across the phonological and the semantic networks as well as the substantial overlap across left frontal, temporal, and parietal regions during phonological and morphological processing (Fig. 3) are also consistent with the notion that since compounds comprise nearly all words in Chinese, compound morphology processing might be especially tightly integrated with other linguistic processes of this language (Zou et al., 2015).

The second finding sheds light on the functionality of left temporal regions for reading in Chinese and across languages. In alphabetic learners, phonological sound-to-print mapping is essential to learning to read. Alphabetic readers' performance and brain activation in left STG regions during phonological awareness tasks such as rhyme judgment is associated with literacy success and dyslexia (Kovelman et al., 2012; Raschle et al., 2012). Yet, this association between left STG functionality during rhyme judgment and literacy success appears less reliable in Chinese (Siok et al., 2008). One possible explanation is that because Chinese readers are less reliant on phonology for reading, the left STG region is less involved in successful literacy acquisition and dyslexia. Yet, it is morphological sensitivity that is especially effective at predicting both literacy success and dyslexia in Chinese (McBride-Chang et al., 2005). A key theoretical explanation for this finding is that awareness of morphosyllabic compounding in Chinese simultaneously taps into core phonological, lexical and other structural characteristics of Chinese, which are critical for spoken as well as written word recognition in the language (Shu, Peng, & McBride-Chang, 2008). Our neuroimaging findings support this perspective by showing that the morphological awareness task elicited robust activation across the language network, including left STG regions classically associated literacy success across languages (Figs. 1 and 3).

More specifically concerning the potential role of left STG in morphological processing, a theoretical neural model of lexical morphology by Cavalli et al. (2016) suggests that the left STG supports the initial decomposition of morphological structures. In other words, the region supports the segmentation of polymorphic items and identification of the constituents' phonological forms and their meanings. The information might then be passed on onto the left inferior frontal areas for recombination and lexico-semantic search of the complete forms. Computationally, deconstructing a typical bi-syllabic Chinese word into constituent morpho-syllables in Chinese may, therefore, be akin to de-constructing a rhyme in a typical mono-syllabic word in English. Current findings are thus consistent with the neural morphological framework that places left STG functionality at a critical juncture of deconstructing Chinese words into morpho-honological constituents and expands our view of the STG as the region that helps segment core structural constituents of a given language. Importantly, we find that in the auditory modality, which precedes and predicts learning to read, the left STG activation was stronger for the morphological than the phonological rhyme judgment task (Fig. 3). Similar to rhyme judgment in English, Chinese children's left STG functionality, as measured with morphological structure awareness tasks, may thus effectively precede and predict reading success in Chinese – a tantalizing hypothesis that would require further investigation.

Our third finding addresses the neural mechanisms that are specific to visual word processing in Chinese. Prior research suggests modality differences between spoken and written language processing. Parietal regions are well known for their role in integrating sensory information and are thought to play a critical role in linking spoken and orthographic language units (Liu et al., 2009; Rueckl et al., 2015). In support of this idea, we find greater parietal activation during the visual than the auditory phonological awareness task (Fig. 2). In contrast, the direct comparison between the auditory and visual morphology conditions did not yield any significant differences beyond the perceptual modality differences. Recall that Chinese characters map onto morphemes and not individual sounds, which might be one reason why the phonology task but not morphology task incurred significantly greater parietal activation during visual word processing. However, it is also note-worthy that frontal activation appeared more extensive during the two visual conditions than during the two auditory conditions, relative to the verbal control tasks (Fig. 1). This observation is consistent with those previously obtained in Chinese and other languages (Siok et al., 2008; Tan et al., 2005), suggesting that visual word processing places greater demands on linguistic as well as attention and working memory resources (Chee et al., 1999; Liuzzi et al., 2017). The latter might be even more extensive for Chinese than alphabetic languages because of the complex nature of character-based orthographic processing (Siok et al., 2008). Nevertheless, a direct comparison between modalities (Fig. 2) and ROI analyses (Fig. 3) did not yield significant differences in activation in the frontal lobe. The overall observation of the present study is that fluent readers of Chinese recruit similar neural mechan-isms for processing words in speech and print, especially during morphological decision tasks.

The present study has several caveats, including a relatively small sample size and experimental measures that were built upon children’s tasks and, therefore, were of low difficulty levels for native Mandarin-speaking adults. The experimental measures were effective at ensuring that the participants had achieved high literacy levels in Chinese yet lacked the sensitivity for discriminating between readers. Additionally, the control task did not include nonword items and may thus have been suboptimal for examining the morphology measure that included both real and pseudowords. This design feature was intended to help isolate morphological structure processes from lexical processes but may have thus also resulted in lexical processing differences between conditions. Nonetheless, these findings are strengthened by their consistency with prior research showing high degree of overlap in activation between phonological and lexico-semantic processing in Chinese (Zhao et al., 2014) as well as extensive left frontal activation during phonological processing in Chinese (Siok et al., 2008), and a greater left parietal activation during the orthographic than auditory phonology tasks (Crottaz-Herbette, Anagnoson, & Menon, 2004).

5. Conclusions and implications

This study explored the neurocognitive bases of Chinese morphological awareness in comparison to phonological awareness, across auditory and visual modalities. The findings revealed greater left temporal activation during morphological than phonological conditions, especially in the auditory modality. In contrast, left frontal activation was strongest during the phonological condition, especially in the visual modality. These results may help to disambiguate the critical role of left temporal regions for Chinese literacy as compared to reading in alphabetic languages. The findings advance the theoretical perspective that morphological awareness is effective at predicting Chinese literacy because it simultaneously taps into the phonological and morphological characteristics of Chinese syllables and characters (Frost, 2012). The findings thus underscore the importance of considering cross-linguistic differences when evaluating language-specific and universal principles of neural organization for processing language in speech and print.

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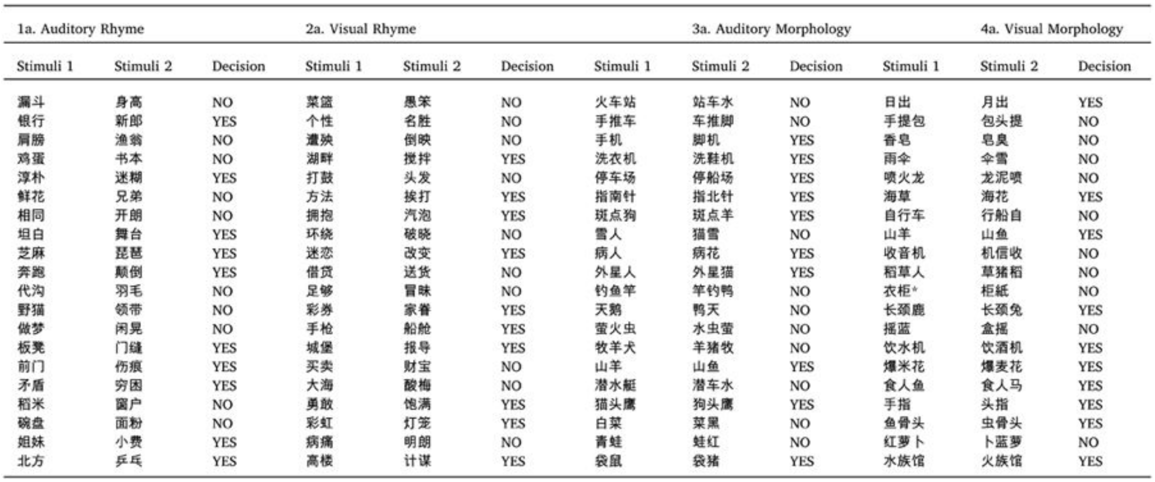
Appendix A

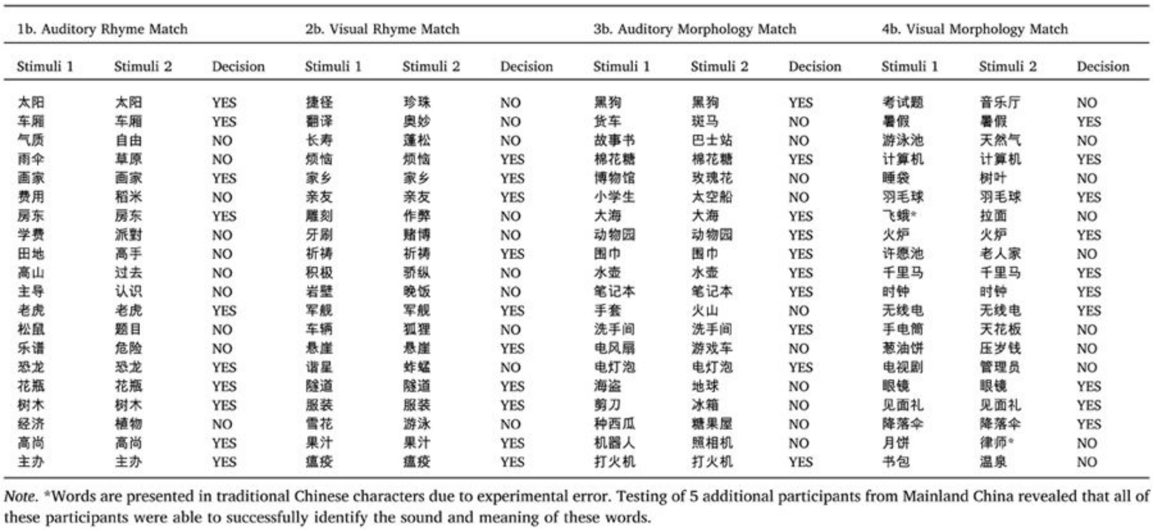
Experimental stimuli for in-scanner behavioral imaging tasks



1a. Auditory Rhyme			2a. Visual Rhyme			3a. Auditory Morphology			4a. Visual Morphology		
Stimuli 1	Stimuli 2	Decision	Stimuli 1	Stimuli 2	Decision	Stimuli 1	Stimuli 2	Decision	Stimuli 1	Stimuli 2	Decision
漏斗	身高	NO	菜篮	愚笨	NO	火车站	站车水	NO	日出	月出	YES
银行	新郎	YES	个性	名胜	NO	手推车	车推脚	NO	手提包	包头提	NO
肩膀	渔翁	NO	遭殃	倒映	NO	手机	脚机	YES	香皂	皂臭	NO
鸡蛋	书本	NO	湖畔	搅拌	YES	洗衣机	洗鞋机	YES	雨伞	伞雪	NO
淳朴	迷糊	YES	打鼓	头发	NO	停车场	停船场	YES	喷火龙	龙泥喷	NO
鲜花	兄弟	NO	方法	挨打	YES	指南针	指北针	YES	海草	海花	YES
相同	开朗	NO	拥抱	汽泡	YES	斑点狗	斑点羊	YES	自行车	行船自	NO
坦白	舞台	YES	环绕	破晓	NO	雪人	猫雪	NO	山羊	山鱼	YES
芝麻	琵琶	YES	迷恋	改变	YES	病人	病花	YES	收音机	机信收	NO
奔跑	颠倒	YES	借贷	送货	NO	外星人	外星猫	YES	稻草人	草猪稻	NO
代沟	羽毛	NO	足够	冒昧	NO	钓鱼竿	竿钓鸭	NO	衣柜*	柜紙	NO
野猫	领带	NO	彩券	家眷	YES	天鹅	鸭天	NO	长颈鹿	长颈兔	YES
做梦	闲晃	NO	手枪	船舱	YES	萤火虫	水虫萤	NO	摇篮	盒摇	NO
板凳	门缝	YES	城堡	报导	YES	牧羊犬	羊猪牧	NO	饮水机	饮酒机	YES
前门	伤痕	YES	买卖	财宝	NO	山羊	山鱼	YES	爆米花	爆麦花	YES
矛盾	穷困	YES	大海	酸梅	NO	潜水艇	潜车水	NO	食人鱼	食人马	YES
稻米	窗户	NO	勇敢	饱满	YES	猫头鹰	狗头鹰	YES	手指	头指	YES
碗盘	面粉	NO	彩虹	灯笼	YES	白菜	菜黑	NO	鱼骨头	虫骨头	YES
姐妹	小费	YES	病痛	明朗	NO	青蛙	蛙红	NO	红萝卜	卜蓝萝	NO
北方	乒乓	YES	高楼	计谋	YES	袋鼠	袋猪	YES	水族馆	火族馆	YES

Appendix B

Word-match control stimuli for in-scanner behavioral imaging tasks



1b. Auditory Rhyme Match			2b. Visual Rhyme Match			3b. Auditory Morphology Match			4b. Visual Morphology Match		
Stimuli 1	Stimuli 2	Decision	Stimuli 1	Stimuli 2	Decision	Stimuli 1	Stimuli 2	Decision	Stimuli 1	Stimuli 2	Decision
太阳	太阳	YES	捷径	珍珠	NO	黑狗	黑狗	YES	考试题	音乐厅	NO
车厢	车厢	YES	翻译	奥妙	NO	货车	斑马	NO	暑假	暑假	YES
气质	自由	NO	长寿	蓬松	NO	故事书	巴士站	NO	游泳池	天然气	NO
雨伞	草原	NO	烦恼	烦恼	YES	棉花糖	棉花糖	YES	计算机	计算机	YES
画家	画家	YES	家乡	家乡	YES	博物馆	玫瑰花	NO	睡袋	树叶	NO
费用	稻米	NO	亲友	亲友	YES	小学生	太空船	NO	羽毛球	羽毛球	YES
房东	房东	YES	雕刻	作弊	NO	大海	大海	YES	飞蛾*	拉面	NO
学费	派對	NO	牙刷	赌博	NO	动物园	动物园	YES	火炉	火炉	YES
田地	高手	NO	祈祷	祈祷	YES	围巾	围巾	YES	许愿池	老人家	NO
高山	过去	NO	积极	骄纵	NO	水壶	水壶	YES	千里马	千里马	YES
主导	认识	NO	岩壁	晚饭	NO	笔记本	笔记本	YES	时钟	时钟	YES
老虎	老虎	YES	军舰	军舰	YES	手套	火山	NO	无线电	无线电	YES
松鼠	题目	NO	车辆	狐狸	NO	洗手间	洗手间	YES	手电筒	天花板	NO
乐谱	危险	NO	悬崖	悬崖	YES	电风扇	游戏车	NO	葱油饼	压岁钱	NO
恐龙	恐龙	YES	谐星	蚱蜢	NO	电灯泡	电灯泡	YES	电视剧	管理员	NO
花瓶	花瓶	YES	隧道	隧道	YES	海盗	地球	NO	眼镜	眼镜	YES
树木	树木	YES	服装	服装	YES	剪刀	冰箱	NO	见面礼	见面礼	YES
经济	植物	NO	雪花	游泳	NO	种西瓜	糖果屋	NO	降落伞	降落伞	YES
高尚	高尚	YES	果汁	果汁	YES	机器人	照相机	NO	月饼	律师*	NO
主办	主办	YES	瘟疫	瘟疫	YES	打火机	打火机	YES	书包	温泉	NO

Note. *Words are presented in traditional Chinese characters due to experimental error. Testing of 5 additional participants from Mainland China revealed that all of these participants were able to successfully identify the sound and meaning of these words.

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Statement of significance

Our morphological task findings suggest that left temporal regions are selectively sensitive to *salient characteristics* of Chinese, the morpho-syllabic units and their orthographic representations. The findings, therefore, inform neurocognitive theories of reading by lending specificity to the universal and language-specific mechanisms of Chinese literacy.

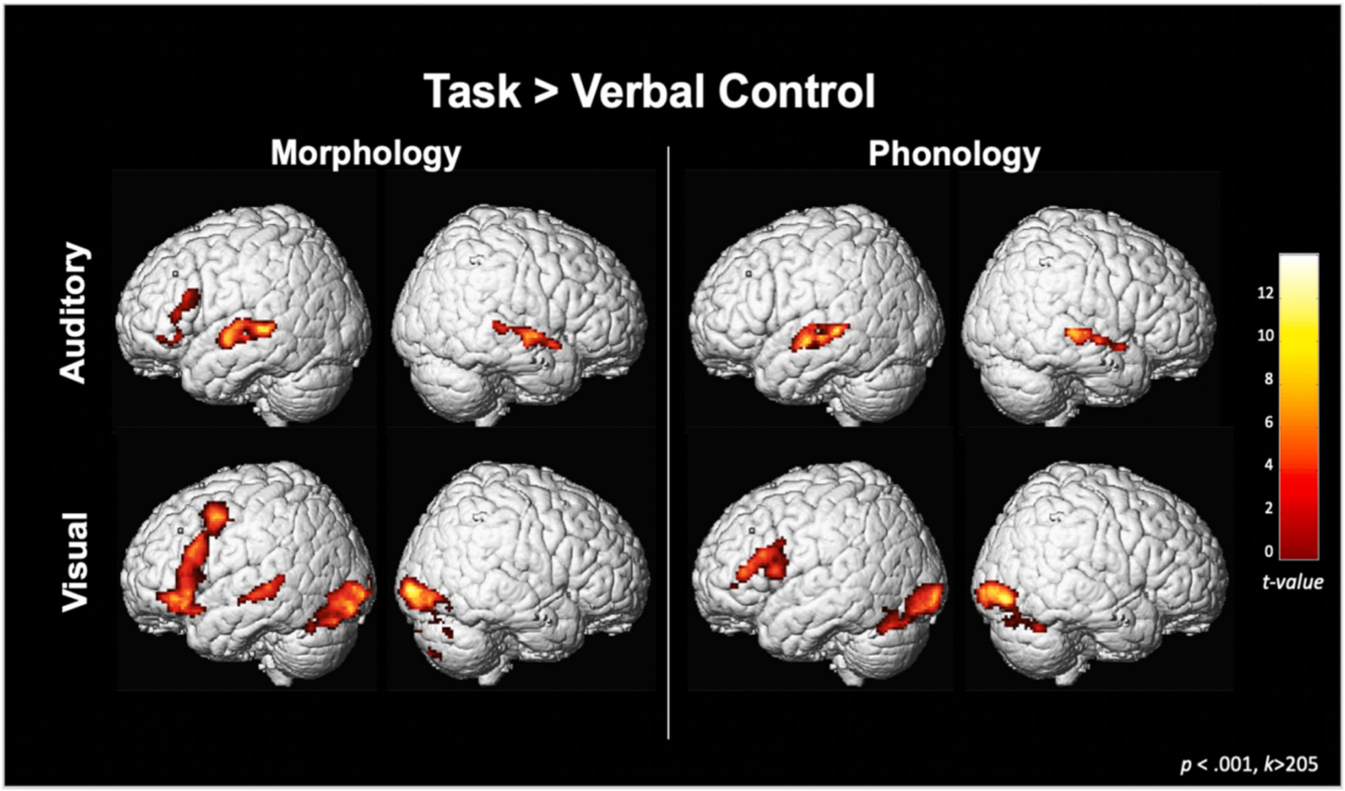
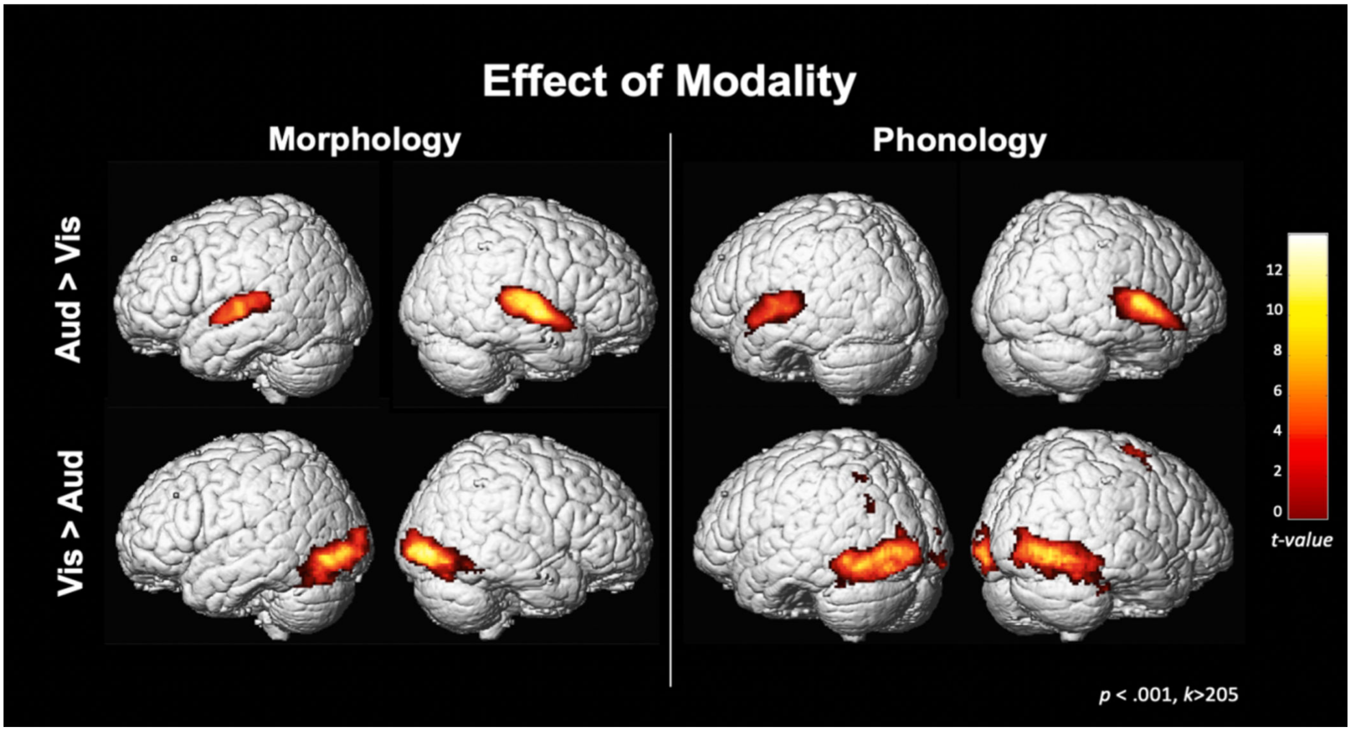

Task > Verbal Control
Morphology
Phonology
Auditory
Visual
12
10
8
6
4
2
0
t-value
p < .001, k>205

Fig. 1.

Whole brain analyses of experimental task versus verbal control.


Effect of Modality
Morphology
Phonology
Aud > Vis
Vis > Aud
12
10
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t-value
p < .001, k>205

Fig. 2.

Brain bases of modality (auditory versus visual) effect. Note. Vis = visual modality; Aud = auditory modality.

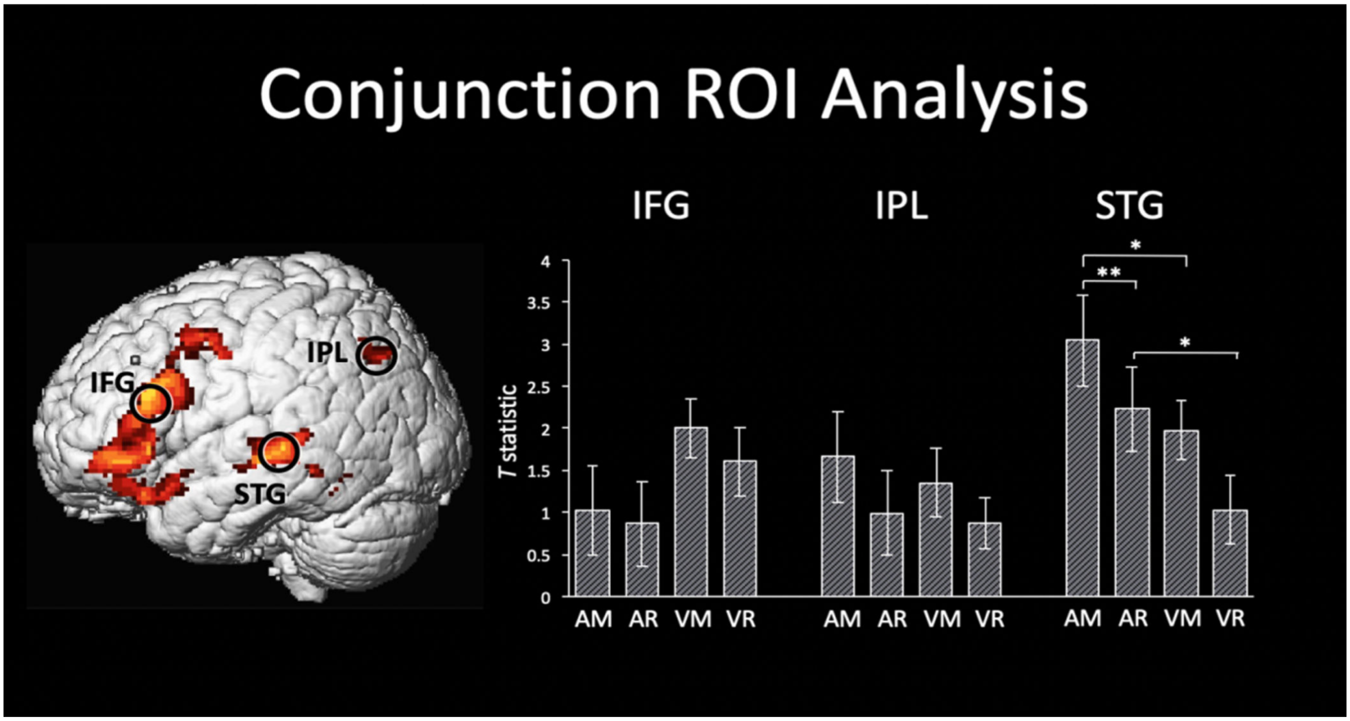

Fig. 3.
Conjunction ROI analyses and comparison of ROI activations. Note. AM = auditory morphology; AR = auditory rhyme; VM = visual morphology; VR = visual rhyme.

Table 1

Behavioral Tasks (N = 14).

Task	Mean ± SD
Age (years)	23.64 ± 3.03
Behavioral Measures	
Orthographic Judgment[2]	0.98 ± 0.02
CTOPP Elision Percentage	0.95 ± 0.04
Reading Fluency RT	168.2 ± 17.78
Reading Fluency Percentage	0.95 ± 0.07
Digit Span Forward Percentage[1]	0.99 ± 0.02
Digit Span Backward Percentage[1]	0.82 ± 0.11
In-Scanner Task Performance	
Auditory	
Accuracy	
Phonological Awareness	0.89 ± 0.14
Morphological Awareness	0.97 ± 0.03
Control for Phonology	0.97 ± 0.03
Control for Morphology	0.96 ± 0.05
Reaction time (ms)	
Phonological Awareness	1953.51 ± 160.74
Morphological Awareness	1683.89 ± 251.84
Control for Phonology	1695 ± 208.55
Control for Morphology	1416.97 ± 262.53
Visual	
Accuracy	
Phonological Awareness	0.89 ± 0.09
Morphological Awareness	0.98 ± 0.02
Control for Phonology	0.98 ± 0.04
Control for Morphology	0.99 ± 0.02
Reaction Time (ms)	
Phonological Awareness	1297.93 ± 325.66
Morphological Awareness	1279.96 ± 313.60
Control for Phonology	990.33 ± 345.66
Control for Morphology	977.53 ± 287.56

Table 2

Peak activation (MNI coordinates) during morphological and phonological processing in the auditory and visual modalities.

		Peak MNI coordinates				
Contrast/Regions	**BA**	***x***	***y***	***z***	***T***	**Voxels**
Auditory Morphology > Control						
Left STG/MTG	22	−64	−28	2	10.74	859
Right STG/MTG	21	60	−8	−6	8.21	499
Left IFG (triangularis)	46	−52	30	12	5.98	342
Visual Morphology > Control						
Left MOG/FG	17	−16	−88	−8	9.22	2327
Left IFG (triangularis)/MFG	46	−48	22	26	8.70	2466
Right cerebellum, ITG, MOG		10	−74	−34	8.65	1902
Left STG/MTG	21	−60	−32	−2	7.03	435
Auditory Phonology > Control						
Left STG/MTG	21	−58	−8	−4	7.15	662
Right STG/MTG	21	56	−28	0	8.36	349
Left MFG, IFG	46	−48	24	32	6.72	88
Visual Phonology > Control						
Right cerebellum, ITG, MOG		42	−58	−28	9.58	1864
Left IOG, MOG	18	−26	−98	−8	7.69	1207
Left IFG (opercularis)	44	−50	16	12	8.14	927
Left IFG (orbitalis)	47	−42	24	−4	6.34	192
Right IFG (orbitalis)	47	44	28	−6	7.79	124

Note. FWE corrected, $p < 0.001$. Coordinates defined by the Montreal Neurological Institute (MNI).

STG, superior temporal gyrus; MTG, middle temporal gyrus; IFG, inferior frontal gyrus; MFG, middle frontal gyrus; MOG, middle occipital gyrus; FG, fusiform gyrus; ITG, inferior temporal gyrus; IOG, inferior occipital gyrus.