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Cultural Constraints on Brain Development: Evidence from a Developmental Study of Visual Word Processing in Mandarin Chinese

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Developmental differences in phonological and orthographic processing in Chinese were examined in 9 year olds, 11 year olds, and adults using functional magnetic resonance imaging. Rhyming and spelling judgments were made to 2-character words presented sequentially in the visual modality. The spelling task showed greater activation than the rhyming task in right superior parietal lobule and right inferior temporal gyrus, and there were developmental increases across tasks bilaterally in these regions in addition to bilateral occipital cortex, suggesting increased involvement over age on visuo-orthographic analysis. The rhyming task showed greater activation than the spelling task in left superior temporal gyrus and there were developmental decreases across tasks in this region, suggesting reduced involvement over age on phonological representations. The rhyming and spelling tasks included words with conflicting orthographic and phonological information (i.e., rhyming words spelled differently or nonrhyming words spelled similarly) or nonconflicting information. There was a developmental increase in the difference between conflicting and nonconflicting words in left inferior parietal lobule, suggesting greater engagement of systems for mapping between orthographic and phonological representations. Finally, there were developmental increases across tasks in an anterior (Broadman area [BA] 45, 46) and posterior (BA 9) left inferior frontal gyrus, suggesting greater reliance on controlled retrieval and selection of posterior lexical representations.

Keywords: Chinese, development, rhyming, spelling

Introduction

The prominent theory argues that reading acquisition relies on the mapping from orthography to phonology, and that a word's meaning will become accessible via the existing phonology-to-semantics link in the oral language system (Chall 1979; Perfetti 1987). However, spoken Chinese is highly homophonic, with a single syllable shared by many characters, the major graphic unit in Chinese. Thus, when learning to read, a Chinese child is confronted with the fact that a large number of written characters correspond to the same syllable, and phonological information is insufficient to access semantics of a printed character. In order to access meaning, the direct connection between orthography and semantics is efficient in Chinese, and therefore orthographic processing is very important. Another reason that the direct connection between orthography and semantics is critical is that 80% of Chinese characters contain semantic radicals that are parts of characters that provide a clue to meaning (e.g., category). There are also phonetic radicals, but most of them (61%) provide inconsistent information regarding pronunciation (Shu et al. 2003). Moreover, the mapping between the phonetic radical and phonology is at a syllabic level and does not involve grapheme-phoneme-correspondences. Therefore, the orthography-semantics connection appears to be robust in Chinese whereas the orthography-phonology connection is relatively weak.

Quite a few studies have suggested that visual skills are important for successful reading acquisition in Chinese (Huang and Hanley 1995; Ho and Bryant 1999; Siok and Fletcher 2001; Tan et al 2005b). A variety of visual skills have been demonstrated to be related to reading across studies, including visual sequential memory (choosing the form presented on a first card among 4 forms on a second card) in first and second graders (Siok and Fletcher 2001), constancy of shapes (detecting particular shapes embedded in and mixed with other visually distracting figures) in 4 year olds (Ho and Bryant 1999), and visual spatial relationships (discriminate a form that is presented in a different orientation from 4 forms of identical configuration) in 10 year olds (McBride-Chang et al. 2005). These findings suggest that in learning to read, it is important for children to engage a visual strategy that notices the salient visual features and spatial relationships with which the features are conjoined, in order to distinguish one character from another. Evidence additionally suggests that orthographic skills are better predictors than phonological skills for reading achievement in Chinese (Ho et al. 2002, 2004, 2007).

Even though studies suggest that both orthographic and phonological representations become more involved with reading experience (Shu 1997; Jiang and Peng 1999; Xu et al. 2004), many studies have suggested that the reliance on phonology may decrease with age, whereas the reliance on orthography may increase with age during reading. This might be due to the fact that there are many homophones in Chinese which makes the connection from phonology to semantics unreliable unless modulated by orthography. One study compared adults with fifth graders during a semantic judgment task (Peng et al. 1985). It was found that it was harder for adults to make a "no" response when the target had similar orthography to a character that was semantically related to the prime than when the target was homophonic to a character that was semantically related to the prime. In contrast, fifth-grade children showed no difference when making "no" responses to these 2 types of stimuli. This suggests that adults rely more on orthography than on phonology as compared to children. Another study explored a more complete developmental course by additionally including younger, third graders (Song et al. 1995). It was found that during proof-reading, third graders were less sensitive to errors that were homophonic to the target character, whereas adults were less sensitive to errors that were orthographically similar to the target. Fifth graders were equally sensitive to both types of errors. This shows that third graders tend to think that a character is correct if the phonology is correct, whereas adults tend to think a character is correct if the orthography is correct. These findings suggest that third graders rely more on phonological information during reading, while adults rely more on orthographic information, with a shift from phonology reliance to orthography reliance at around fifth grade. In addition, an ERP study using sentence reading found that children with lower reading skill (third grade to sixth grade) exhibit greater phonology-reliance than those with higher reading skill (Meng et al. 2007).

Neuroimaging studies in adults have also suggested that visuo-orthographic processing is crucial in Chinese reading compared to English reading, and that the visual analyses in Chinese engage bilateral temporo-occipital regions while those in English mainly engage the left hemisphere (Petersen et al. 1989; Bookheimer et al. 1995; Chee et al. 1999; Cohen et al. 2000; Liu and Perfetti 2003; Bolger et al 2005; Tan et al. 2005a; Cao et al. 2009; Kuo et al. 2001; Xue et al. 2005). Greater involvement of right temporo-occipital regions in Chinese might be due to the special features of Chinese characters. The Chinese character is composed of strokes and subcharacter components (also called radicals) that are packed into a square configuration, resulting in high, nonlinear visual spatial complexity (Chen and Kao 2002) which requires greater holistic visuo-spatial analysis (Liu and Perfetti 2003). The right hemisphere is more involved in holistic processing of visual information whereas the left hemisphere is more involved in feature detection and analysis (Jonides et al. 1993; Smith et al. 1995). Additionally, previous studies have found less involvement of left superior temporal gyrus (STG) in Chinese than in English (Bolger et al. 2005; Tan et al. 2005a). This might be due to the fact that syllabic structure is simpler in Chinese than in English, because all characters are monosyllabic and Chinese writing does not encourage phoneme representations due to the fact that no part of the character corresponds to phonemes. Altogether, studies suggest that visuo-orthographic analysis in right temporo-occipital regions plays a more important role in Chinese reading, whereas phonological processing in left STG plays a more important role in English reading.

Previous neuroimaging studies have also suggested that there are 3 brain regions that seem to be essential for both English and Chinese reading. The first region is anterior inferior frontal gyrus (aIFG) including Broadman Area (BA) 45/46 which has been found to be more activated in phonological tasks than in orthographic tasks in both English (Herbster et al. 1997; Rumsey et al. 1997) and Chinese (Tan et al. 2000; Kuo et al. 2004). The anterior region of the IFG has been implicated in controlled retrieval of lexical representations (Badre et al. 2005; Badre and Wagner 2007; Lau et al. 2008). The second region is dorsal left inferior frontal gyrus (IFG) including BA 9/44 which has been found to be more activated for inconsistent or irregular words compared to consistent or regular words in both English (Fiez et al. 1999; Bolger et al. 2008) and Chinese (Tan et al. 2001; Peng et al. 2003; Lee et al. 2004). Dorsal left IFG has been implicated in lexical selection between active candidates (Badre et al. 2005; Badre and Wagner 2007; Lau et al. 2008). The last region common to Chinese and English is left inferior parietal lobule (IPL) which has been found to be more activated in tasks that involve mapping between orthography and phonology as compared to those that do not, suggesting its involvement in integrating orthographic and phonological representations (Booth et al. 2002, 2006; Liu et al. 2009). In addition, these 3 regions have been found to be involved to a greater degree for word pairs with conflicting orthographic and phonological information (i.e., words with similar orthography but different phonology, e.g., pint-mint, and words with different orthography but similar phonology, e.g., jazz-has) than for those with nonconflicting information (i.e., words with similar orthography and similar phonology, e.g., gate-hate, and words with different orthography and different phonology, e.g., press-list) (Bitan, Cheon, et al. 2007; Cone et al. 2008).

The current study explored developmental changes of brain activation during orthographic and phonological processing of Chinese visual words in third graders, fifth graders, and adults. Based on behavioral research and due to the unique qualities of the Chinese orthographic and phonological systems, we expected to see developmental increases in activation in visuo-orthographic processing regions including bilateral temporo-occipital cortex, but a developmental decrease in activation of regions involved in auditory phonological representations including left STG. Based on developmental neuroimaging research in English, we expected to see developmental increases in regions involved in controlled retrieval and selection including left IFG. We were also interested in examining how developmental changes would be affected by task difficulty. In the more difficult conditions, orthographic and phonological information was conflicting, whereas in the easier conditions, this information was nonconflicting. In the conflicting conditions, words either had similar orthography and different phonology or different orthography and similar phonology (see Table 1). In Chinese, similar phonology was defined as the same rhyme for the second character in the word and similar orthography was defined as the same phonetic radical in the second character in the word. As with neuroimaging studies in English (Booth et al. 2007; Bitan, Burman, et al. 2007), we expected to see greater developmental increases in left IPL for conflicting than for nonconflicting conditions in Chinese.

Methods

Participants

Twenty adults (*M* age = 21.5, range 19–28, 7 males) participated in the rhyming and spelling tasks. Seventeen third-grade children (*M* age = 9.2, range: 8–10; 8 males) participated in the rhyming and 16 third-grade children (*M* age = 9.2, range: 8–10; 9 males) participated in the spelling task. Twelve of them participated in both tasks. Fifteen fifth-grade children (*M* age = 11.5, range: 10–12; 8 males) participated in the rhyming and 19 fifth-grade children (*M* age = 11.5, range: 10–12; 10 males) participated in the spelling task. Fourteen of them participated in both tasks. According to an informal interview given to adults or parents of children, all participants met the following criteria: 1) native Mandarin Chinese speaker, 2) right-handed, 3) free of neurological disease or psychiatric disorders, 4) no attention deficit hyperactivity disorder, and 5) no learning disability.

Table 1
Examples of stimuli in four conditions (O+P+, O+P-, O-P+, O-P-).

	Orthography similar	Orthography different
Phonology similar	围绕/wei2rao3/-发烧/ fa1shao1/(O+P+)	钞票/chao1piao4/- 医疗/yi1liao2/(O-P+)
Phonology different	皮鞋/pi2xie2/-泥娃/ ni2wa2/ (O+P-)	压缩//ya1suo1- 傍晚/bang4wan3/(O-P-)

Cognitive Tasks

Rhyming and Spelling Tasks

Two words were presented sequentially in the visual modality and participants were asked to determine whether the second character of the 2 words rhyme in the rhyming judgment or whether the second character of the 2 words had a similar orthography by sharing a phonetic radical in the spelling judgment. All words consisted of 2 characters. We manipulated the similarity of the orthography and phonology of the second character of the first and the second word. Thus, we had 4 conditions (see Table 1): characters with similar orthography that rhyme (O+P+), characters with similar orthography that do not rhyme (O+P–), characters with different orthography that rhyme (O–P+) and characters with different orthography that do not rhyme (O–P–). There were 24 trials in each condition. In 12 trials, the second character of the first and the second word had the same tone (e.g. 弥补/bu3/, 纯朴/pu3/), in the other 12 trials, they had different tones (e.g. 逮捕/bu3/, 胸脯/pu2/). Tone was manipulated because Chinese children are exposed to pairs of words that rhyme, but have different tones (Shu et al. 2003).

Stimulus Characteristics

All words used in this experiment did not have homophones. The 2-character words were matched on several variables across tasks, conditions, and presentation orders using ANOVA models of 2 task (rhyming and spelling) × 4 condition (O+P+, O+P–, O–P+, and O–P–) × 2 presentation order (first word and second word). These variables were adult written frequency (Beijing Language and Culture University, 1990), number of strokes, word familiarity in third graders, and word familiarity in fifth graders. Word familiarity was assessed in an independent study on 50 third graders and 50 fifth graders through a 7-point scale.

The second characters of words were also matched on several variables across tasks, conditions, and presentation orders using ANOVA models of 2 task (rhyming and spelling) × 4 condition (O+P+, O+P–, O–P+, and O–P–) × 2 presentation order (first word and second word). The variables were adult written frequency (Beijing Language and Culture University, 1990), number of strokes, and consistency. Phonological consistency (Bolger et al. 2008) was matched across tasks and across the presentation order, but not across conditions. Words in the O+P– condition had significantly lower phonological consistency than words in the other 3 conditions ($t(46) = 5.022$, $P = 0.000$ for O+P+, $t(46) = 6.836$, $P = 0.000$ for O–P+, and $t(46) = 8.117$, $P = 0.000$ for O–P–).

Perceptual Control Tasks

For the perceptual control task, 2 of the same Tibetan symbols were visually presented side by side following another 2 Tibetan characters. The participant was asked to judge whether the 2 patterns were the same or not. For example, ཐིཐི and ཐིཐི were the same, while ཐིཐི and ཆཆ were different. The perceptual control task had 24 trials with half of them the same and half different. All participants reported no exposure to Tibetan to ensure that Tibetan characters would serve as an appropriate perceptual control task. Tibetan was chosen because it is similar to Chinese characters in terms of visual complexity and configuration.

There were also 48 null trials in which a black cross turns red indicating the need to press a button with the right index finger.

Experimental Procedure

We used an event-related design with 4 6-min 44-s runs including 2 runs of each task. In each run, there were 48 experimental trials, 12 control trials, and 24 null trials. Stimuli of each run were presented in the same order for all participants, optimized using OptSeq (http://surfer.nmr.mgh.harvard.edu/optseq). The administration of the 2 tasks was counterbalanced across participants who took part in both tasks. In each run, there was a 12-s equilibration period at the beginning, and a 22-s period at the end in order to be able to deconvolve the whole hemodynamic response function (HRF) for the last trial. In each trial, 2 consecutive 2-character words were visually presented with the first word presented for 800 ms followed by a 200-ms blank interval and the second word presented for 800 ms. A red fixation cross (+) appeared on the screen after the second word, indicating the need to make a response during the subsequent 2200-ms interval. Control trials were presented with the same procedure as the experimental trials. For null trials, there was a black fixation cross (+) presented for 1800 ms and then a red cross was presented for 2200 ms.

MRI Data Acquisition

After informed consent was obtained, the informal interview was administered. The participant then practiced a half-length version of the experimental task to become familiarized with the tasks. Different stimuli (matched in their stimulus characteristics) were used in the practice and functional magnetic resonance imaging (fMRI) sessions. If the subject's accuracy rate was higher than 60% during the practice, they were allowed to participate in the fMRI experiment within the subsequent week.

All images were acquired using a 3-Tesla Siemens scanner. Gradient-echo localizer images were acquired to determine the placement of the functional slices. For the functional imaging studies, a susceptibility weighted single-shot EPI (echo planar imaging) method with blood oxygenation level–dependent was used. Functional images were interleaved from bottom to top in a whole brain EPI acquisition. The following scan parameters were used: time repetition (TR) = 2000 ms, time echo (TE) = 20 ms, flip angle = 80°, matrix size = 128 × 128, field of view = 220 mm, slice thickness = 3 mm, number of slices = 33. These scanning parameters resulted in a 1.7 × 1.7 × 3 mm voxel size. At the end of the functional imaging session, a high resolution, T_1-weighted 3-dimensional image was acquired (magnetization-prepared rapid gradient-echo, TR = 2390 ms, TE = 2.9 ms, time inversion [TI] = 900 ms, flip angle = 20°, matrix size = 256 × 256, field of view = 256 mm, slice thickness = 1 mm, number of slices = 160). The orientation of the 3D volume was identical to the functional slices.

Image Data Analysis

Data analysis was performed using SPM5 (Statistical Parametric Mapping) (http://www.fil.ion.ucl.ac.uk/spm). The functional images were corrected for differences in slice-acquisition time to the middle volume and were realigned to the last volume in the scanning session using affine transformations. No individual runs had more than 4 mm maximum movement for any subject in the *x*-plane (in the rhyming task: $M = 0.44$, range = 0.08–1.57 for the adults; $M = 0.34$, range = 0.07–0.84 for the third graders; $M = 0.31$, range = 0.11–0.87 for the fifth graders; in the spelling task: $M = 0.37$, range = 0.07–1.62 for the adults; $M = 0.33$, range = 0.13–0.73 for the third graders; $M = 0.45$, range = 0.11–3.19 for the fifth graders), *y*-plane (in the rhyming task: $M = 0.96$, range = 0.25–2.17 for the adults; $M = 0.77$, range = 0.23–1.48 for the third graders; $M = 0.80$, range = 0.32–1.70 for the fifth graders; in the spelling task: $M = 0.91$, range = 0.25–2.77 for the adults; $M = 1.08$, range = 0.41–1.90 for the third graders; $M = 1.09$, range = 0.35–2.42 for the fifth graders) or *z*-plane (in the rhyming task: $M = 0.97$, range = 0.24–2.55 for the adults; $M = 0.70$, range = 0.38–3.91 for the third graders; $M = 1.50$, range = 0.42–2.38 for the fifth graders; in the spelling task: $M = 1.04$, range = 0.15–3.33 for the adults; $M = 1.58$, range = 0.32–3.62 for the third graders; $M = 1.89$, range = 0.27–3.66 for the fifth graders). Furthermore, no individual runs had more than 3° of maximum displacement in rotation for pitch, yaw, or roll. An ANOVA with group and task as independent variables showed no significant main effects or interactions on any of these 6 dependent variables. All statistical analyses were conducted on movement-corrected images. Coregistered images were normalized to the Montreal Neurological Institute average template (12 linear affine parameters for brain size and position, 8 nonlinear iterations, and 2 × 2 × 2 nonlinear basis functions). Statistical analyses were calculated on the smoothed data (4 × 4 × 8 mm Gaussian kernel).

Data from each subject were entered into a general linear model using an event-related analysis procedure. Word pairs were treated as individual events for analysis and modeled using a canonical HRF. Statistics were calculated with a high-pass filter (128-s cutoff period). We used global normalization to scale the mean of each scan to a common value. Parameter estimates from contrasts of the canonical HRF in single subject models were entered into random-effects analyses. All whole brain results are reported at $P < 0.001$ uncorrected and contain 10 or greater voxels.

In order to determine overall group and task differences, we employed ANCOVA of group (adults, children) by task (rhyming, spelling) with accuracy on task as a covariate on the contrast of lexical (all 4 conditions combined: O+P+, O+P–, O–P+, O–P–) minus null. Because third graders and fifth graders showed similar brain activation patterns, we combined them in the comparison to adults. In order to determine if any of the developmental effects in lexical processing were due to differences in low-level visual processing, we used the same ANCOVA model above for the perceptual control minus null with a mask of the significant developmental effects in the lexical minus null contrast.

In order to investigate differences between the third and fifth graders, we examined 11 volumes of interest (VOIs) based on the developmental effects (adults versus the combined group of children) on the lexical minus null ANCOVA reported above. We extracted beta values (6 mm radius sphere) from these VOIs for each age group in each task. The 11 VOIs were dorsal IFG (dIFG), IPL, and STG in the left hemisphere and aIFG, superior parietal lobule (SPL), inferior temporal gyrus (ITG), and middle occipital gyrus (MOG) in the left and right hemispheres. We combined the bilateral homologues of aIFG, SPL, ITG, and MOG, because neither the developmental effect nor task effect had a significant interaction with laterality in ANOVA of group (adults, third graders, fifth graders) by task (rhyming, spelling) by laterality (left, right). Thus we had 7 ROIs in the following analysis. Then we calculated an ANCOVA of group (adults, third graders, and fifth graders) by task (rhyming and spelling) with accuracy as a covariate for each of the 7 ROIs to determine developmental and task differences.

In order to determine developmental differences in the conflict effect, we compared adults to children on the contrast of conflicting (combined O+P– and O–P+) minus nonconflicting (combined O+P+ and O–P–) for each lexical task in a whole brain analysis. In order to illustrate these effects, we extracted beta values for each of the 4 lexical conditions in each group in each task in 2 VOIs that showed conflict effect in the whole brain analysis—left IFG and left IPL.

Results

Behavioral Performance

Table 2 presents accuracy and reaction time for adults and children on the rhyming, spelling, and control trials in the scanner. We calculated task (rhyming, spelling, and control) by group (adults, third graders, and fifth graders) ANOVAs separately for accuracy and reaction time on correct trials. There were significant main effects of group for accuracy, $F_{2,43} = 24.855$, $P < 0.001$, and reaction time, $F_{2,43} = 15.017$, $P < 0.001$. There were significant main effects of task for accuracy, $F_{2,86} = 64.759$, $P < 0.001$, and reaction time, $F_{2,86} = 39.353$, $P < 0.001$.

Multiple comparisons for the task effect found that the accuracy on the spelling and control tasks was significantly higher than that on the rhyming task ($t(45) = 6.759$, $P < 0.001$, $t(51) = 7.651$, $P < 0.001$, respectively). Reaction time on the spelling and control tasks was also significantly faster than that on the rhyming task ($t(45) = -2.417$, $P = 0.02$, $t(51) = -11.004$, $P < 0.001$, respectively). The difference between the spelling and control tasks was not significant for accuracy ($t(54) = 0.232$, $P = 0.817$), but significant for reaction time with the spelling task slower than the control task ($t(54) = 7.274$, $P < 0.001$).

Multiple comparisons for the developmental effect found that adults were more accurate, $t(39) = 6.104$, $P < 0.001$, and faster $t(39) = -4.929$, $P < 0.001$, than third graders. Adults were also more accurate, $t(38) = 4.832$, $P < 0.001$, and faster $t(38) = -4.448$, $P < 0.001$, than fifth graders. Fifth graders were more accurate than third graders ($t(39) = 2.468$, $P = 0.018$), but as fast as third graders ($t(39) = -0.065$, $P = 0.948$).

There was also a significant interaction between group and task for accuracy, $F_{4,86} = 10.293$, $P < 0.001$, but not for reaction time, $F_{4,86} = 2.325$, $P = 0.063$. Simple effect analysis found that for the rhyming task, adults were more accurate than third graders and fifth graders ($t(35) = 10.007$, $P < 0.001$, $t(33) = 5.043$, $P < 0.001$, respectively), and the fifth graders were more accurate than the third graders ($t(30) = 2.826$, $P = 0.008$). For the spelling task, adults were more accurate than third graders and fifth graders ($t(34) = 4.295$, $P < 0.001$, $t(37) = 2.633$, $P = 0.012$, respectively), but the difference between fifth graders and third graders was not significant ($t(33) = 0.860$, $P = 0.396$). For the control task, adults were more accurate than third graders and fifth graders ($t(39) = 2.333$, $P = 0.025$, $t(38) = 2.175$, $P = 0.036$, respectively), but the difference between fifth graders and third graders was not significant ($t(39) = 0.908$, $P = 0.369$).

Table 3 presents accuracy and reaction time for adults and children on the 4 conditions of the rhyming and spelling tasks. We calculated condition (O+P+, O–P+, O–P+, and O–P–) by group (adults, third graders, and fifth graders) ANOVAs separately for accuracy and reaction time in each task. There were significant main effects of condition for accuracy ($F_{3,147} = 5.976$, $P = 0.001$ for the rhyming task; $F_{3,156} = 5.918$, $P = 0.001$ for the spelling task), and for reaction time ($F_{3,147} = 5.281$, $P = 0.002$ for the rhyming task, $F_{3,156} = 8.917$, $p < 0.001$ for the spelling task). There were significant main effects of group for accuracy ($F_{2,49} = 26.829$, $P < 0.001$ for the rhyming task; $F_{2,52} = 6.411$, $P = 0.003$ for the spelling task), and for reaction time ($F_{2,49} = 14.599$, $P < 0.001$ for the rhyming task; $F_{2,52} = 4.727$, $P = 0.013$ for the spelling task).

Multiple comparisons between conditions found that for the rhyming task, accuracy on O–P– was significantly higher than

Table 2

Means (and SD) for accuracy and reaction time for adults and children in the rhyming, spelling and control trials

	Rhyming	Spelling	Control
Accuracy (%)			
Third graders	71.3 (9.5)	91.9 (5.7)	91.4 (12.5)
Fifth graders	81.3 (10.6)	93.7 (6.6)	94.4 (7.3)
Adults	93.9 (3.3)	97.7 (1.8)	98.1 (2.2)
Reaction time (ms)			
Third graders	1730 (237)	1415 (237)	1262 (232)
Fifth graders	1712 (294)	1395 (229)	1273 (219)
Adults	1227 (324)	1202 (237)	965 (193)

Table 3

Means (and SD) for accuracy and reaction time for adults and children in different conditions of the rhyming and spelling tasks

Accuracy (%)	O+P+	O+P−	O−P+	O−P−
Rhyming				
Third graders	68.3 (15.1)	65.8 (24.2)	67.9 (14.4)	78.7 (17.4)
Fifth graders	80.7 (19.5)	76.9 (18.3)	75.5 (18.4)	84.5 (16.2)
Adults	95.8 (3.9)	93.2 (7.3)	89.6 (7.8)	97.9 (2.6)
Reaction time (ms)				
Third graders	1500 (242)	1657 (376)	1725 (337)	1638 (240)
Fifth graders	1640 (275)	1795 (342)	1688 (322)	1726 (330)
Adults	1214 (360)	1253 (339)	1234 (315)	1210 (324)
Spelling				
Third graders	93.6 (7.1)	89.1 (10.5)	89.3 (9.9)	96.2 (4.2)
Fifth graders	96.3 (3.9)	92.3 (8.8)	93.2 (11.3)	93.4 (5.9)
Adults	97.9 (3.8)	97.0 (3.4)	97.7 (2.9)	98.8 (2.7)
Reaction time (ms)				
Third graders	1437 (270)	1384 (211)	1143 (268)	1393 (220)
Fifth graders	1328 (236)	1364 (233)	1457 (279)	1437 (255)
Adults	1132 (243)	1176 (268)	1248 (232)	1252 (267)

that on O+P+, O+P–, and O–P+ ($t(51) = 2.113$, $P = 0.04$, $t(51) = 4.279$, $P < 0.001$, $t(51) = 3.999$, $P < 0.001$, respectively). Accuracy on O+P+ was significantly higher than that on O–P+ ($t(51) = 3.133$, $P = 0.003$). Reaction time on O+P+ was significantly faster than that on O+P–, O–P+, and O–P– ($t(51) = 3.565$, $P = 0.001$, $t(51) = 2.480$, $P = 0.016$, $t(51) = 2.369$, $P = 0.022$, respectively). For the spelling task, accuracy on O+P+ was significantly higher than that on O+P– and O–P+ ($t(54) = 2.949$, $P = 0.005$, $t(54) = 2.257$, $P = 0.028$, respectively). Accuracy on O–P– was significantly higher than that on O+P– and O–P+ ($t(54) = 2.771$, $P = 0.008$, $t(54) = 2.441$, $P = 0.018$, respectively). Reaction time on O+P+ was significantly faster than that on O–P+, and O–P– ($t(54) = 4.570$, $P < 0.001$, $t(54) = 2.994$, $P = 0.004$, respectively). Reaction time on O+P– was significantly faster than that on O–P+ and O–P– ($t(54) = 4.147$, $P < 0.001$, $t(54) = 2.333$, $P = 0.002$, respectively).

The interaction between group and condition was not significant on the rhyming task either for accuracy ($F_{6,147} = 0.556$, $P = 0.764$) or for reaction time ($F_{6,147} = 1.962$, $P = 0.075$). The interaction between group and condition was not significant on the spelling task for accuracy ($F_{6,156} = 1.974$, $P = 0.073$), but was significant for reaction time ($F_{6,156} = 2.663$, $P = 0.017$). Simple effect analysis found that adults were faster than third graders and fifth graders on O+P+ ($t(34) = 3.561$, $P = 0.001$, $t(37) = 2.540$, $P = 0.015$, respectively), O+P– $t(34) = 2.536$, $P = 0.016$, $t(37) = 2.331$, $P = 0.025$, respectively), and O–P+ $t(34) = 2.347$, $P = 0.025$, $t(37) = 2.488$, $P = 0.017$, respectively). Adults were faster than fifth graders but not third graders on O–P– ($t(37) = 2.207$, $P = 0.034$, $t(34) = 1.693$, $P = 0.100$, respectively). The differences between third graders and fifth graders were not significant for O+P+,O+P–, O–P+, or O–P– ($t(33) = 1.283$, $P = 0.208$, $t(33) = 0.264$, $P = 0.793$, $t(33) = 0.090$, $P = 0.929$, $t(33) = 0.543$, $P = 0.591$, respectively).

Brain Activation Patterns

Task Effects

Table 4 shows the effect of task across all groups, and Figure 1 shows the brain activation maps for rhyming minus spelling (green) and spelling minus rhyming (red). The rhyming task invoked greater activation than the spelling task in left STG, while the spelling task invoked greater activation than the rhyming task in right SPL and right inferior temporal gyrus.

Developmental Effects

Table 4 shows developmental differences across the 2 tasks, and Figure 2 shows the brain activation maps for adults minus children (green) and children minus adults (red). Adults showed greater activation than children in bilateral anterior inferior frontal gyri (BA 45/46), left dIFG (BA 9), bilateral SPL (BA 7), left IPL (BA 40), bilateral middle occipital gyrus (BA 18/19), and bilateral inferior temporal gyri extending into fusiform gyrus (BA 37). Children showed greater activation than adults in left STG (BA 22).

There were no developmental differences in the contrast of perceptual control minus null using the developmental differences in lexical minus null as a mask, suggesting that all developmental differences in lexical minus null are due to lexical rather than perceptual processing.

Table 4

Direct comparisons between the rhyming and the spelling task, as well as between children and adults

Contrast	Region	H	BA	*z*-Test	Voxels	*x*	*y*	*z*
Rhyming > spelling	STG	L	42, 22	5.21	11	−52	−42	18
Spelling > rhyming	SPL, precuneus	R	7, 19	4.14	96	30	−60	40
	Inferior temporal gyrus, fusiform gyrus	R	19, 37	3.87	39	48	−52	−10
Adults > children	Cuneus, middle occipital gyrus	R	18, 19	5.47	826	28	−80	32
	Middle occipital gyrus, superior occipital gyrus, precuneus	L	19, 7	5.02	406	−26	−86	6
	Cuneus, inferior occipital gyrus	R	18, 19	4.84	67	20	−90	2
	Middle temporal gyrus	L	37, 20	4.96	103	−56	−62	−6
	Inferior temporal gyrus, middle temporal gyrus, fusiform gyrus	L	37	4.17	40	−50	−54	−14
	Middle temporal gyrus	L	37	4.56	28	−48	−74	14
	Inferior temporal gyrus, middle temporal gyrus, fusiform gyrus	R	37	4.71	147	50	−56	−10
	SPL	L	7	4.59	237	−24	−60	62
	Precuneus, SPL	R	7	3.94	69	20	−56	52
	IPL	L	40	3.95	29	−34	−32	38
	IPL	L	40	3.90	61	−28	−56	40
	aIFG	L	46, 45	4.37	32	−50	34	18
	dIFG	L	9	4.10	55	−46	8	34
	Postcentral gyrus	L	2, 1	3.81	81	−44	−30	34
	aIFG	R	46	3.84	23	48	34	18
Children > adults	STG	L	42, 22	3.65	11	−54	−42	16
	Declive	L	—	4.83	38	−44	−64	−28

Note: Peaks of activation are listed in bold for areas spanning different regions; H = hemisphere, L = left, R = right; BA = Brodmann's area.

Interaction

We found an interaction between task and group only in an extra-nuclear area ($x = 20$, $y = 28$, $z = 6$, cluster = 13) for lexical minus null.

VOI Analysis

Developmental effects in lexical minus null were used to identify 11 VOIs including left anterior IFG (−50, 34, 18), right anterior IFG (48, 34, 18), left SPL (−24, −60, 62), right SPL (30, −56, 44), left ITG (−56, −62, −6), right ITG (50, −56, −10), left MOG (−26, −86, 6), right MOG (20, −90, 2), left dorsal IFG (−46, 8, 34), left IPL (−46, 8, 34), and left STG (−54, −42, 16). A group (adults, third graders, and fifth graders) by task (rhyming and spelling) by laterality (left and right) ANOVA for each region with bilateral homologues revealed no significant interactions with laterality, therefore homologues in the 2 hemispheres for anterior IFG, SPL, ITG, and MOG were combined into one measure, which left 7 VOIs in the following analysis.

A group (adults, third graders, and fifth graders) by task (rhyming and spelling) ANCOVA was calculated for each region with accuracy as a covariate. Figure 3 presents brain activation at the 7 VOIs for each group in each task. Significant main effects of task were found in left STG ($F_{1,45} = 28.637$, $P < 0.001$) with rhyming greater than spelling, in bilateral ITG ($F_{1,45} = 18.336$, $P < 0.001$) and bilateral SPL ($F_{1,45} = 5.243$, $P = 0.027$) with spelling greater than rhyming. Significant group effects were found in left IPL ($F_{2,57} = 6.360$, $P = 0.003$), left dIFG ($F_{2,57} = 5.209$, $P = 0.008$), bilateral aIFG ($F_{2,57} = 7.243$, $P = 0.002$), bilateral ITG ($F_{2,57} = 5.596$, $P = 0.006$), bilateral MOG ($F_{2,57} = 9.574$, $p < 0.001$), and bilateral SPL ($F_{2,57} = 7.916$, $P = 0.001$). Multiple comparisons found that adults were greater than the third graders in all of these VOIs ($t(39) = 2.083$,

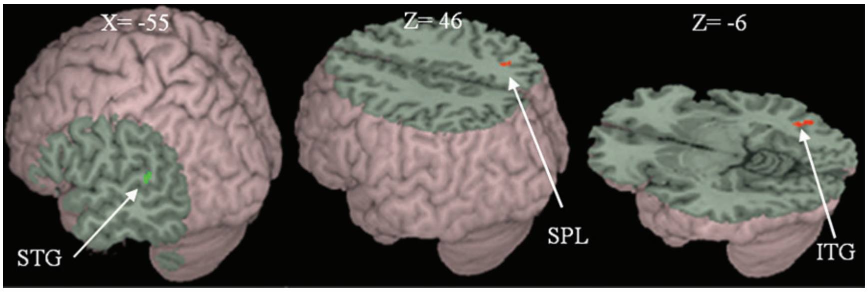

Figure 1. Task effects across all age groups. The rhyming task (green) produced greater activation than the spelling task in left STG, while the spelling task (red) produced greater activation than the rhyming task in right SPL and right ITG.

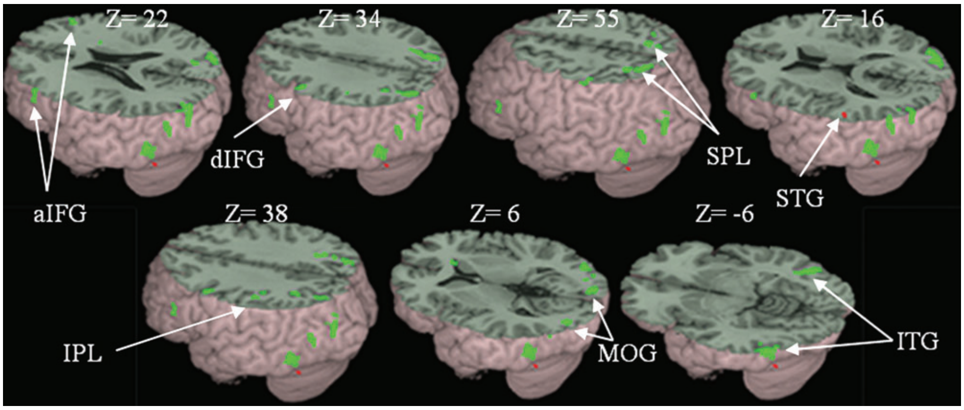

Figure 2. Developmental changes across the 2 lexical tasks. Adults (green) showed greater activation than children in left dIFG, bilateral aIFG, bilateral SPL, left IPL, bilateral MOG and bilateral ITG. Children (red) showed greater activation than adults in left STG.

$P = 0.044$ for left IPL; $t(39) = 3.869$, $P < 0.001$ for left dIFG; $t(39) = 3.495$, $P = 0.001$ for bilateral aIFG; $t(39) = 3.869$, $P < 0.001$ for bilateral ITG; $t(39) = 2.934$, $P = 0.006$ for bilateral MOG; $t(39) = 4.253$, $P < 0.001$ for bilateral SPL). Adults showed greater activation than fifth graders in all these VOIs except left IPL ($t(38) = 3.891$, $P = 0.000$ for left dIFG; $t(38) = 3.455$, $P = 0.001$ for bilateral aIFG; $t(38) = 3.891$, $P < 0.001$ for bilateral ITG; $t(38) = 4.276$, $P < 0.001$ for bilateral MOG; $t(38) = 3.298$, $P = 0.002$ for bilateral SPL). Fifth graders and third graders were not significantly different in for all these VOIs.

The only significant interaction between task and group was left STG ($F_{2,42} = 3.583$, $P = 0.037$). Simple effect analysis found that group difference on the rhyming task was significant ($F_{2,48} = 3.496$, $P = 0.038$). Multiple comparisons found that the activity for third graders was significantly greater than adults ($t(35) = 2.347$, $P = 0.025$). The difference between third graders and fifth graders was not significant ($t(30) = 0.811$, $P = 0.424$), nor was the difference between fifth graders and adults ($t(33) = 1.459$, $P = 0.154$). Group differences on the spelling task was significant ($F_{2,51} = 4.183$, $P = 0.021$). Multiple comparisons found that the activity in fifth graders was significantly greater than that in adults ($t(37) = 2.393$, $P = 0.022$), but that the difference between third graders and adults was not significant ($t(34) = 0.207$, $P = 0.837$), nor was the difference between third graders and fifth graders ($t(33) = -1.868$, $P = 0.071$).

Conflict Effects

Table 5 shows regions that showed greater conflict effects (conflicting conditions vs. nonconflicting conditions) in adults than in children for the rhyming and the spelling tasks. Figure 4 shows the brain activation maps for these comparisons and, for illustrative purposes, the brain activation patterns at these regions for each group in each condition for the rhyming and the spelling tasks. Adults showed greater conflict effect in left IPL and right IFG for the rhyming task; in left IPL and left IFG for the spelling task.

Discussion

Increased Reliance on Visuo-orthographic Processing

The current study found that the spelling task evoked greater activation in right SPL and right inferior temporal gyrus than the rhyming task. Previous studies have suggested that bilateral SPL is involved in visual spatial analysis in mental rotation (Cohen et al. 1996; Alivisatos and Petrides 1997) and shifting of spatial attention (LaBar et al 1999). Our spelling task required explicit visual comparison of radicals within the character which involves greater visual spatial analysis and spatial attention than the rhyming task. Previous studies have also found that left inferior temporo-occipital area is associated with orthographic representation and rapid visual word form recognition (Petersen et al. 1989; Bookheimer et al. 1995; Cohen et al. 2000), while the right temporo-occipital area is involved in nonlinguistic visual configuration (Turkeltaub et al. 2003). Our finding of greater activation in right inferior temporal gyrus for the spelling task than for the rhyming task might be due to the greater involvement of nonlinguistic visual configuration processing.

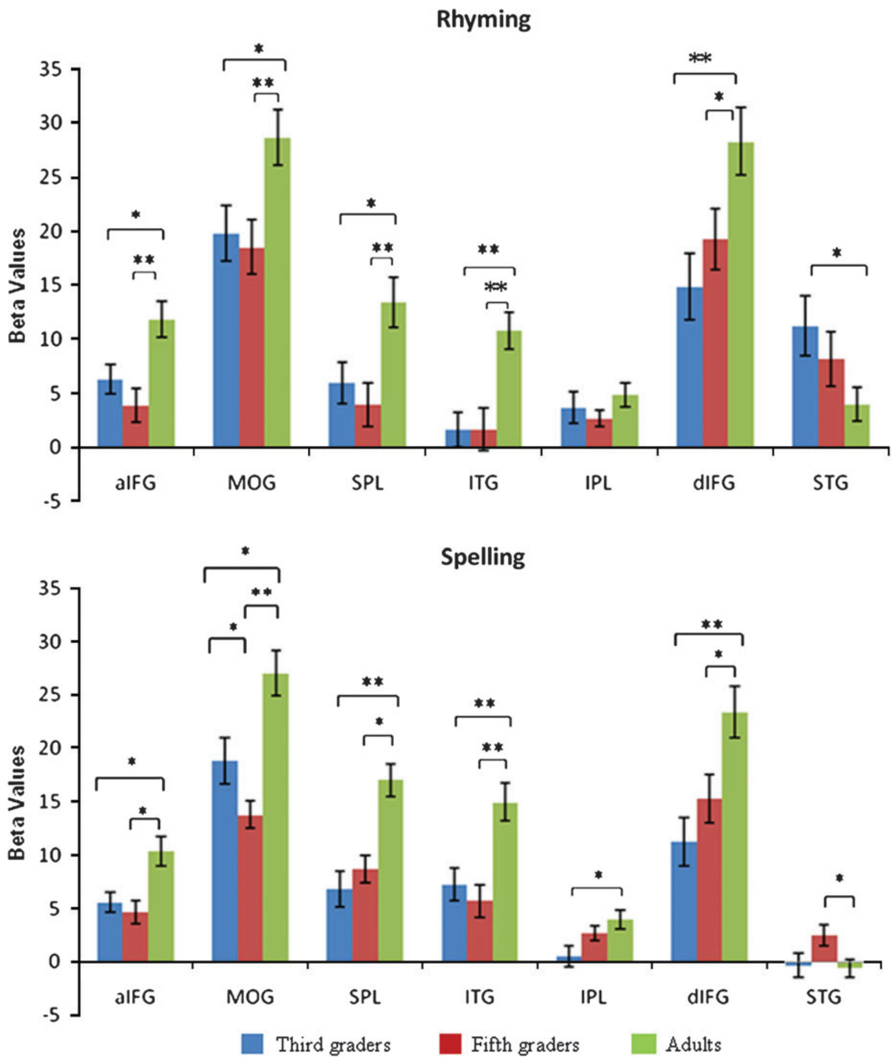

Figure 3. Beta values at 7 VOIs in each group of participants on the rhyming and spelling tasks. One asterisk indicates significant group differences at $P < 0.05$, and 2 asterisks indicate significant differences at $P < 0.01$. aIFG = bilateal IFG, MOG = bilateral MOG, SPL = bilateral SPL, ITG = bilateral ITG, dIFG = left dIFG, IPL = left IPL, STG = left STG.

Table 5

Greater conflict effects (O+P− and O−P+ vs. O+P+ and O−P−) in adults than in children for the rhyming and spelling tasks

Contrast	Region	H	BA	*z*-Test	Voxels	*x*	*y*	*z*
Rhyming	IFG	R	47	4.26	35	34	20	−4
	IPL	L	40	3.53	18	−36	−50	44
	Culmen	R	—	3.98	19	36	−48	−32
Spelling	IFG	L	45, 46	3.90	12	−54	34	8
	IPL	L	40	3.28	11	−36	−60	48

Note: Peaks of activation are listed in bold for areas spanning different regions; H = hemisphere, L = left, R = right; BA = Brodmann's area.

We found developmental increases in bilateral SPL, bilateral inferior temporal gyrus, and bilateral middle occipital gyrus across the rhyming and the spelling tasks. However, none of these regions showed developmental differences for the perceptual control task, suggesting that the developmental effects are restricted to Chinese character processing. The developmental increase in these regions for visual character processing suggests that adults have more elaborated spatial analysis in SPL, more elaborated orthographic representation in inferior temporal gyrus, and more elaborated visual analysis in middle occipital gyrus as compared to children. This is consistent with a previous study that found a developmental increase in right middle occipital gyrus for a phonological and a semantic task to visually presented words in Chinese (Cao et al. 2009).

English studies have also found developmental increases or skill-related increases in orthographic analysis regions for visual word processing, but mostly in the left hemisphere, such as left inferior temporal gyrus or left fusiform gyrus (Bitan et al. 2009; Shaywitz et al. 2007). English studies have also shown developmental decreases in right inferior temporal cortex in a spelling judgment task (Booth et al. 2004) and an implicit reading task (Turkeltaub et al. 2003). These findings suggest that in English visual word processing, there is a developmental increase in the specialization of orthographic processing to the left fusiform gyrus, while there is a developmental decrease in nonlinguistic visual spatial analysis in the right hemisphere. However, in Chinese, there appears to be a developmental increase in visuo-orthographic analysis in both hemispheres. Substantial developmental increases in bilateral visuo-orthographic regions seem to be a neural signature of Chinese

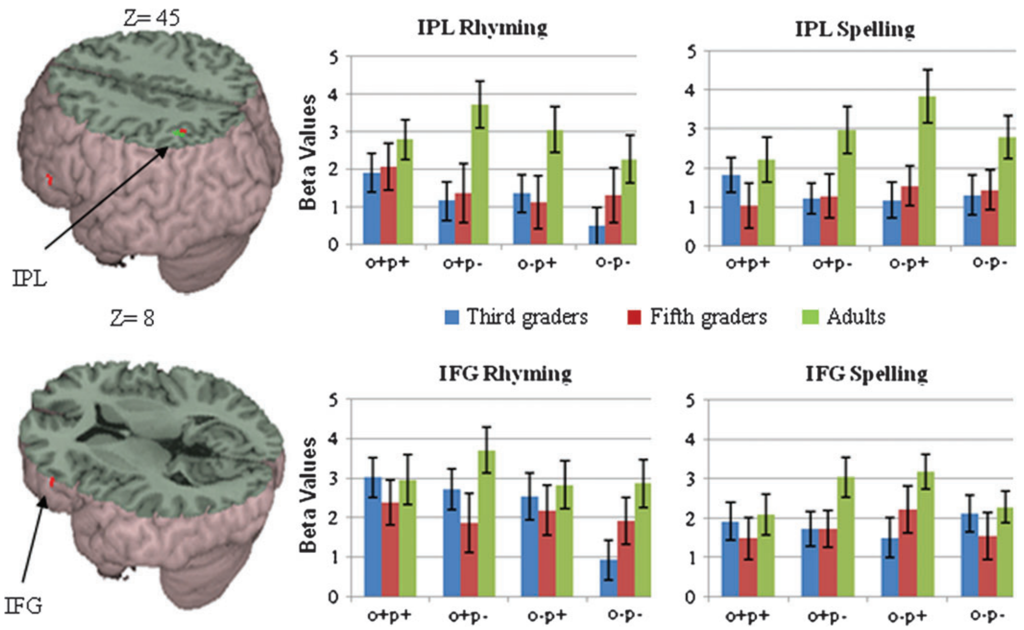

Figure 4. Developmental differences in conflict effects in the rhyming (green) and spelling (red) task. Adults showed greater conflict effect (2 conflicting conditions vs. 2 nonconflicting conditions) than children in left IPL for both tasks and in left IFG for the spelling task. Bar graphs present the beta values of IPL and IFG in each group for each condition in the rhyming and the spelling task.

reading development that has never been demonstrated in alphabetic writing systems.

Decreased Reliance on Phonology in Superior Temporal Cortex

The current study found that the rhyming task evoked greater activation in left STG than the spelling task, suggesting the involvement of this region in phonological processing. We also found developmental decreases in this region, especially for the rhyming task. This is consistent with a previous English study that found a developmental decrease in activation of left STG during a visual rhyming task (Bitan, Cheon, et al. 2007). Developmental decreases in left STG for Chinese is consistent with behavioral findings of reduced reliance on phonological information with age and reading skill. For example, it was found that in comparison to college students and sixth-grade children, third-grade children exhibit greater Stroop effects for homophonic conditions (e.g., 洪/hong2/-flood in the color of green vs. 洪/hong2/-flood in the color of red. 洪 is homophonic to 红/hong2/-red.), suggesting greater activation of phonology in third-grade children (Guo et al. 2005).

Our study provides neuroimaging evidence for the argument that reading development of Chinese is characterized by increased reliance on orthography and decreased reliance on phonology (Meng et al. 2007; Peng et al. 1985; Song et al. 1995). This phenomenon might also be true in English (Pugh et al. 2000; Church et al. 2008), but it is much more salient in Chinese (Perfetti et al. 2005). This is because the existence of multi-homophony in Chinese makes it more efficient to access meaning through the connection between orthography and semantics rather than the connection of orthography to phonology to semantics. Quite a few studies have suggested that phonology plays a less important role in Chinese than it does in English (Leck et al. 1995; Feng et al. 2001; Zhou and Marslen-Wilson 2000). For example, Leck et al. (1995) asked participants to decide whether a character (e.g. 狐/hu2/-fox) belonged to a defined semantic category (animal). They found that both orthographically similar nonhomophonic characters (呱/gua1/-) and orthographically similar homophonic characters (弧/hu2/-arch) were harder to reject than neutral controls, while orthographically dissimilar homophonic characters (湖/hu2/-lake) were not significantly different from controls. This suggests that phonology alone will not efficiently activate meaning in Chinese reading. For the first year of school, children are taught pinyin, an alphabetic system for Chinese pronunciation, and they use pinyin to facilitate learning to read. After the first year, children learn without the help of pinyin. With further reading experience, children reduce their reliance on pinyin and/or pinyin coded phonology and develop more direct connections between orthography and meaning (Song et al. 1995). We studied third and fifth graders so presumably the influence of pinyin should be minimal. Therefore, high reading proficiency appears to be associated with a tighter connection between orthography and semantics, while low reading proficiency appears to be associated with phonologically mediated access of meaning.

We found no difference between third graders and fifth graders except for right middle occipital gyrus which showed greater activation in third graders (9 year olds) than in fifth graders (11 year olds). One previous study found that Chinese children with dyslexia (11 year olds) showed greater activation in right inferior occipital gyrus than typically achieving children during a visual lexical decision task (Siok et al. 2004). Therefore, children with dyslexia and younger children tend to show greater activation in this region than typically achieving and older children, suggesting greater effort in orthographic processing. Lack of differences between third graders and fifth graders in other regions might be due to the nature of the tasks in the current study. Greater developmental differences in reliance on orthography versus phonology might be seen in more natural reading tasks, such as proof-reading, as shown in behavioral studies (Song et al. 1995; Meng et al 2008).

Conflict Effects in IPL

We found developmental increases in the conflict effect, with greater activation over age in left IPL for conflicting conditions compared to nonconflicting conditions in both the rhyming and spelling tasks. This region sensitive to developmental differences in the conflict effect overlaps with the developmental increase in left IPL across all lexical conditions. Left IPL has been implicated in the mapping between orthography and phonology (Booth et al. 2002, 2006; Chen et al. 2002). It may be involved to a greater degree when the orthographic and phonological information is conflicting, because remapping between these 2 representational systems might be necessary for a correct response. Previous English studies have found conflict effects in this region using the same paradigm (i.e. O+P+, O+P–, O–P+, O–P–) in a visual rhyming task and a visual spelling task (Bitan, Burman, et al. 2007). Another study found developmental increases in left IPL across all lexical conditions in a visual rhyming judgment task and activation of this region for the contrast of conflicting versus nonconflicting conditions positively correlated with accuracy in the conflicting conditions (Bitan, Cheon, et al. 2007). Our finding suggests that this mapping system is involved to a greater degree in adults than in children when the orthographic and phonological information is conflicting.

An alternative interpretation is that the developmental increases in left IPL and IFG are due to age-related changes in the working memory system. Both of these regions are involved in working memory (LaBar et al. 1999) and a previous study has shown that adults have greater sensitivity than children to memory load in these regions (O'Hare et al. 2008). In our study, adults may have shown greater activation than children in these regions in the contrast of conflicting minus nonconflicting because the conflicting conditions have greater memory load due to interfering orthographic and phonological information.

Developmental Changes in Anterior and Dorsal Frontal Regions

Many previous studies have found developmental increases in anterior left IFG (BA 45/46/47) in a variety of lexical tasks (Shaywitz et al. 2002; Gaillard et al. 2003; Turkeltaub et al. 2003; Holland et al. 2007). Consistent with this, we found developmental increases in activation of anterior left IFG (BA 45/46) across the rhyming and spelling tasks. We also found that there was a developmental increase in the conflict effect with greater activation for conflicting than for nonconflicting conditions in anterior left IFG (BA 45/46) during the spelling task. This is consistent with previous English studies that found conflict effects in left IFG (BA 45/46) in a visual rhyming task (Bitan, Burman, et al. 2007), an auditory rhyming task (Cone et al. 2008), and an auditory spelling task (Booth et al. 2007). Studies have suggested that anterior left IFG is involved in controlled retrieval of lexical representations in posterior cortex based on top-down information (Badre et al. 2005; Badre and Wagner 2007; Lau et al. 2008). Our finding of increased activation in left IFG and simultaneous decreased activation in left STG (see Discussion above) indicates developmental increases in top-down control which may result in reduced activation of irrelevant phonological representations in posterior cortex, and is consistent with a previous study in English (Bitan, Cheon, et al. 2007). The lack of top-down control in younger children may result in greater activation of irrelevant phonological representations in superior temporal cortex.

We also found developmental increases in the activation of dorsal left IFG (BA 9) for both tasks. This region has been implicated in the selection between active representations that have been activated (Badre et al. 2005; Badre and Wagner 2007; Lau et al. 2008). Even though this region has been found to be involved in both English and Chinese, some researchers argue that it is more consistently and strongly activated in Chinese (Bolger et al. 2005; Tan et al. 2005a; Chen et al. 2008). An important feature about Chinese character processing is that mapping from phonology to semantics is very context-dependent, because of the large number of homophones. Access of correct semantics has to involve a selection mechanism based on orthography. Moreover, this region has been found to be associated with reading skills in Chinese children. Siok et al. (2004) found that children with poor reading skills showed reduced activation in left BA 9 in a homophone judgment and lexical decision task to visually presented words compared to children with normal reading skills. Cao et al also found skill-related increase in BA 9 within Chinese children (10–12 years old) during a visual rhyming task (Cao et al. 2009). However, previous English studies have also established developmental increases in dorsal left IFG during a visual rhyming and visual spelling task (Bitan, Cheon, et al. 2007). Although there may be language differences in the involvement of dorsal left IFG, the present study and previous research suggests developmental and skill-related increases in the engagement of selection mechanisms during lexical processing.

Conclusions

The current study provides neuroimaging evidence for the argument that reading development in Chinese is characterized by increasing reliance on brain areas involved in visuo-orthographic processing and those involved in mapping between orthographic and phonological representations, with concomitant decreases in reliance on phonology in superior temporal cortex. The decreased reliance on phonology may be a result of increased controlled retrieval and selection mechanisms in inferior frontal cortex.

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Notes

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References

Alivisatos B, Petrides M. 1997. Functional activation of the human brain during mental rotation. Neuropsychologia. 35:111–118.

Badre D, Poldrack RA, Pare-Blagoev EJ, Insler RZ, Wagner AD. 2005. Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. Neuron. 47:907–918.

Badre D, Wagner AD. 2007. Left ventrolateral prefrontal cortex and the cognitive control of memory. Neuropsychologia. 45:2883–2901.

Bitan T, Burman DD, Chou TL, Dong L, Cone NE, Cao F, Bigio JD, Booth JR. 2007. The interaction of orthographic and phonological

information in children: an fMRI study. Hum Brain Mapp. 28:880–891.
Bitan T, Cheon J, Lu D, Burman DD, Booth JR. 2009. Developmental increase in top-down and bottom-up processing in a phonological task: an effective connectivity, fMRI study. J Cogn Neurosci. 21: 1135–1145.
Bitan T, Cheon J, Lu D, Burman DD, Gitelman DR, Mesulam MM, Booth JR. 2007. Developmental changes in activation and effective connectivity in phonological processing. Neuroimage. 38:564–575.
Bolger D, Hornickel J, Cone N, Burman D, Booth J. 2008. Neural correlates of orthographic and phonological consistency effects in children. Hum Brain Mapp. 29:1416–1429.
Bolger DJ, Perfetti CA, Schneider W. 2005. Cross-cultural effect on the brain revisited: universal structures plus writing system variation. Hum Brain Mapp. 25:92–104.
Bookheimer SY, Zeffiro TA, Blaxton T, Gaillard W, Theodore W. 1995. Regional cerebral blood flow during object naming and word reading. Hum Brain Mapp. 3:93–106.
Booth JR, Burman DD, Meyer JR, Gitelman DR, Parrish TR, Mesulam MM. 2002. Functional anatomy of intra- and cross-modal lexical tasks. Neuroimage. 16:7–22.
Booth JR, Burman DD, Meyer JR, Zhang L, Gitelman DR, Parrish TR, Mesulam MM. 2004. Development of brain mechanisms for processing orthographic and phonological representations. J Cogn Neurosci. 16:1234–1249.
Booth JR, Cho S, Burman DD, Bitan T. 2007. Neural correlates of mapping from phonology to orthography in children performing an auditory spelling task. Dev Sci. 10:441–451.
Booth JR, Lu D, Burman DD, Chou TL, Jin Z, Peng DL, Zhang L, Ding GS, Deng Y, Liu L. 2006. Specialization of phonological and semantic processing in Chinese word reading. Brain Res. 1071:197–207.
Cao F, Peng D, Liu L, Jin Z, Fan N, Deng Y, Booth JR. 2009. Developmental differences of neurocognitive networks for phonological and semantic processing in Chinese word reading. Hum Brain Mapp. 30:797–809.
Chall JS. 1979. The great debate: Ten years later, with a modest proposal for reading stages. In: Resnick LB, Weaver PA, editors. Theory and practice of early reading. Hillsdale, NJ: Erlbaum. p. 29–55.
Chee MW, Caplan D, Soon CS, Sriram N, Tan EW, Thiel T, Weekes B. 1999. Processing of visually presented sentences in Mandarin and English studied with fMRI. Neuron. 23:127–137.
Chen X, Kao HSR. 2002. Visual-spatial properties and orthographic processing of Chinese characters. In: Kao HSR, editor. Cognitive neuroscience studies of the Chinese language. Aberdeen, Hong Kong: Hong Kong University Press. p. 175–194.
Chen HC, Vaid J, Bortfeld H, Boas DA. 2008. Optical imaging of phonological processing in two distinct orthographies. Exp Brain Res. 184:427–433.
Chen Y, Fu S, Iversen SD, Smith SM, Matthews PM. 2002. Testing for dual brain processing routes in reading: a direct contrast of Chinese character and pinyin reading using FMRI. J Cogn Neurosci. 14: 1088–1098.
Church JA, Coalson RS, Lugar HM, Petersen SE, Schlaggar BL. 2008. A developmental fMRI study of reading and repetition reveals changes in phonological and visual mechanisms over age. Cereb Cortex. 18:2054–2065.
Cohen L, Dehaene S, Naccache L, Lehericy S, Dehaene-Lambertz G, Henaff MA, Michel F. 2000. The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. Brain. 123:291–307.
Cohen MS, Kosslyn SM, Breiter HC, DiGirolamo GJ, Thompson WL, Anderson AK, Bookheimer SY, Rosen BR, Belliveau JW. 1996. Changes in cortical activity during mental rotation: a mapping study using functional MRI. Brain. 119:89–100.
Cone NE, Burman DD, Bitan T, Bolger DJ, Booth JR. 2008. Developmental changes in brain regions involved in phonological and orthographic processing during spoken language processing. Neuroimage. 41:623–635.
Feng G, Miller K, Shu H, Zhang H, Kkue Miller. 2001. Rowed to recovery: the use of phonological and orthographic information in reading Chinese and English. J Exp Psychol Learn Mem Cogn. 27:1079–1100.
Fiez JA, Balota DA, Raichle ME, Petersen SE. 1999. Effects of lexicality, frequency, and spelling-to-sound consistency on the functional anatomy of reading. Neuron. 24:205–218.
Gaillard WD, Sachs BC, Whitnah JR, Ahmad Z, Balsamo LM, Petrella JR, Braniecki SH, McKinney CM, Hunter K, Xu B, et al. 2003. Developmental aspects of language processing: fMRI of verbal fluency in children and adults. Hum Brain Mapp. 18:176–185.
Guo T, Peng D, Liu Y. 2005. The role of phonological activation in the visual semantic retrieval of Chinese characters. Cognition. 98:B21–B34.
Herbster AN, Mintun MA, Nebes RD, Becker JT. 1997. Regional cerebral blood flow during word and nonword reading. Hum Brain Mapp. 5:84–92.
Ho C, Chan DW, Tsang SM, Lee SH. 2002. The cognitive profile and multiple-deficit hypothesis in Chinese developmental dyslexia. Dev Psychol. 38:543–553.
Ho CS, Chan DW, Chung KK, Lee SH, Tsang SM. 2007. In search of subtypes of Chinese developmental dyslexia. J Exp Child Psychol. 97:61–83.
Ho CS, Chan DW, Lee SH, Tsang SM, Luan VH. 2004. Cognitive profiling and preliminary subtyping in Chinese developmental dyslexia. Cognition. 91:43–75.
Ho CS-H, Bryant P. 1999. Different visual skills are important in learning to read English and Chinese. Educ Child Psychol. 16:4–14.
Holland SK, Vannest J, Mecoli M, Jacola LM, Tillema JM, Karunanayaka PR, Schmithorst VJ, Yuan W, Plante E, Byars AW. 2007. Functional MRI of language lateralization during development in children. Int J Audiol. 46:533–551.
Huang HS, Hanley JR. 1995. Phonological awareness and visual skills in learning to read Chinese and English. Cognition. 54:73–98.
Jiang T, Peng DL. 1999. Chinese Phonological awareness of children and the differences between good and poor readers. Acta Psychol Sin. 31:60–68.
Jonides J, Smith EE, Koeppe RA, Awah E, Minoshima S, Mintun MA. 1993. Spatial working memory in humans as revealed by PET. Nature. 363:623–625.
Kuo W, Yeh TC, Lee JR, Chen LF, Lee PL, Chen SS, Ho LT, Hung DL, Tzeng OJ, Hsieh JC. 2004. Orthographic and phonological processing of Chinese characters: an fMRI study. Neuroimage. 21:1721–1731.
Kuo W-J, Yeh T-C, Cuann J-R, Wu T-T, Ho L-T, Hung D, Tzeng O-J, Hsieh J-CI. 2001. A left-lateralized network for reading Chinese words: a 3 T fMRI study. Neuroreport. 12:3997–4001.
LaBar KS, Gitelman DR, Parrish TB, Mesulam MM. 1999. Neuroanatomic overlap of working memory and spatial attention networks: a functional MRI comparison within subjects. Neuroimage. 10:695–704.
Lau EF, Phillips C, Poeppel D. 2008. A cortical network for semantics: (de)constructing the N400. Nat Rev Neurosci. 9:920–933.
Leck KJ, Weekes BK, Chen MJ. 1995. Visual and phonological pathways to the lexicon: evidence from Chinese readers. Mem Cognit. 23:468–476.
Lee C, Tsai J, Kuo W, Yeh T, Wu Y, Ho L, Hung D, Tzeng O, Hsieh J. 2004. Neuronal correlates of consistency and frequency effects on Chinese character naming: an event-related fMRI study. Neuroimage. 23:1235–1245.
Liu L, Deng X, Peng D, Cao F, Ding G, Jin Z, Zeng Y, Li K, Zhu L, Fan N, et al. 2009. Modality- and task-specific brain regions involved in Chinese lexical processing. J Cogn Neurosci. 21:1473–1487.
Liu Y, Perfetti CA. 2003. The time course of brain activity in reading English and Chinese: an ERP study of Chinese bilinguals. Hum Brain Mapp. 18:167–175.
McBride-Chang C, Chow BW-Y, Zhong Y-P, Burgess S, Hayward W. 2005. Chinese character acquisition and visual skills in two Chinese scripts. Read Writing Interdisciplinary J. 18:99–128.
Meng X, Jian J, Shu H, Tian X, Zhou X. 2008. ERP correlates of the development of orthographical and phonological processing during Chinese sentence reading. Brain Res. 1219:91–102.
Meng X, Tian X, Jian J, Zhou X. 2007. Orthographic and phonological processing in Chinese dyslexic children: an ERP study on sentence reading. Brain Res. 1179:119–30.

O'Hare E, Lu LH, Houston SM, Bookheimer SY, Sowell ER. 2008. Neurodevelopmental changes in verbal working memory load-dependency: an fMRI investigation. Neuroimage. 42:1678–1685.
Peng D, Ding G, Perry C, Xu D, Jin Z, Luo Q, Zhang L, Deng Y. 2003. fMRI evidence for the automatic phonological activation of briefly presented words. Cogn Brain Res. 20:156–164.
Peng D, Guo DJ, Zhang SL. 1985. Access to the lexical information of Chinese characters during semantic judgment. Acta Psychol Sin. 3:227–233.
Perfetti CA. 1987. Language, speech, and print: Some asymmetries in the acquisition of literacy. In: Horowitz R, Samuels SJ, editors. Comprehending oral and written language. New York: Academic Press. p. 355–369.
Perfetti CA, Liu Y, Tan LH, Perfetti. 2005. The lexical constituency model: some implications of research on chinese for general theories of reading. Psychol Rev. 112:43–59.
Petersen SE, Fox PT, Posner MI, Mintun M, Raichle ME. 1989. Positron emission tomographic studies of the processing of single words. J Cogn Neurosci. 1:153–170.
Pugh KR, Mencl WE, Jenner AR, Katz L, Frost SJ, Lee JR, Shaywitz SE, Shaywitz BA. 2000. Functional neuroimaging studies of reading and reading disability (developmental dyslexia). Ment Retard Dev Disabil Res Rev. 6:207–213.
Rumsey JM, Horowitz B, Donohue BC, Nace K, Maisog JM, Andreason P. 1997. Phonological and orthographic components of word recognition: a PET-rCBF study. Brain. 120:739–759.
Shaywitz B, Shaywitz S, Pugh K, Mencl E, Fulbright R, Skudlarski P, Constable T, Marcxhione K, Fletcher JM, Lyon GR, et al. 2002. Disruption of posterior brain systems for reading in children with developmental dyslexia. Biol Psychiatry. 52:101–110.
Shaywitz BA, Skudlarski P, Holahan JM, Marchione KE, Constable RT, Fulbright RK, Zelterman D, Lacadie C, Shaywitz SE. 2007. Age-related changes in reading systems of dyslexic children. Ann Neurol. 61:363–370.
Shu H. 1997. Vocabulary acquisition and reading development by Chinese children. In: Peng D, Shu H, Chen H, editors. Research on cognitive processing of chinese language. Qingdao, China: Shandong Education Publishing Co.
Shu H, Chen X, Anderson RC, Wu N, Xuan Y. 2003. Properties of school Chinese: Implications for learning to read. Child Dev. 74: 27–47.
Siok WT, Fletcher P. 2001. The role of phonological awareness and visual-orthographic skills in Chinese reading acquisition. Dev Psychol. 37:886–899.
Siok WT, Perfetti CA, Jin Z, Tan LH. 2004. Biological abnormality of impaired reading is constrained by culture. Nature. 431:71–76.
Smith EE, Jonides J, Koeppe RA, Awh E, Schumacher EH, Minoshima S. 1995. Spatial versus object working memory: PET investigations. J Cogn Neurosci. 7:337–356.
Song H, Zhang HC, Shu H. 1995. Developmental changes in functions of orthography and phonology in Chinese reading. Acta Psychol Sin. 2:139–144.
Tan LH, Feng C-M, Fox PT, Gao J-H. 2001. An fMRI study with written Chinese. Neuroreport Int J Rapid Commun Res in Neurosci. 12: 83–88.
Tan LH, Laird AR, Karl L, Fox PT. 2005. Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: a meta-analysis. Hum Brain Mapp. 25:83–91.
Tan LH, Spinks JA, Eden GF, Perfetti CA, Siok WT. 2005. Reading depends on writing, in Chinese. Proc Natl Acad Sci USA. 102: 8781–8785.
Tan LH, Spinks JA, Gao J-H, Liu H-L, Perfetti CA, Xiong J, Stofer KA, Pu Y, Liu Y, Fox PT. 2000. Brain activation in the processing of Chinese characters and words: a functional MRI study. Hum Brain Mapp. 10:16–27.
Turkeltaub PE, Garaeu L, Flowers DL, Zefirro TA, Eden G. 2003. Development of the neural mechanisms for reading. Nat Neurosci. 6:767–773.
Xu F, Dong Q, Yang J, Wang W. 2004. The development of Children's Chinese phonological awareness. Psychol Sci. 27:18–20.
Xue G, Dong Q, Chen K, Jin Z, Chen C, Zeng Y, Reiman ME. 2005. Cerebral asymmetry in children when reading Chinese characters. Cogn Brain Res. 24:206–214.
Zhou X, Marslen-Wilson W. 2000. The relative time course of semantic and phonological activation in reading Chinese. J Exp Psychol Learn Mem Cogn. 26:1245–1265.