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Cerebral Asymmetry in the Fusiform Areas Predicted the Efficiency of Learning a New Writing System

Gui Xue¹, Chuansheng Chen¹, Zhen Jin², and Qi Dong³

Abstract

■ There are great individual differences in learning abilities, but their neural bases, especially among normal populations, are not well understood. Using functional magnetic resonance imaging and a training paradigm, the present study investigated individual differences in cerebral asymmetry in fusiform regions when processing a new writing system and their correlation to subsequent visual character learning. Twelve Chinese

adults underwent a 2-week training to learn 120 Korean characters and they were scanned before and after the training. Results showed that left-hemispheric dominance during the pretraining task was predictive of better posttraining performance. These results have significant implications for our understanding of the neural basis of language learning, especially in terms of individual differences. ■

INTRODUCTION

Language has long been considered a function of the left hemisphere of the brain. With the advances of functional neuroimaging techniques, recent studies have generally revealed bilateral, although left hemisphere dominated, activation during most language tasks (e.g., Frost et al., 1999; Pujol, Deus, Losilla, & Capdevila, 1999; Binder, Swanson, et al., 1996; Binder, Rao, et al., 1995; Desmond et al., 1995). Furthermore, by quantifying neural activation in the two hemispheres, researchers have identified significant variations in cerebral language asymmetry among normal, right-handed adults (Tzourio-Mazoyer, Josse, Crivello, & Mazoyer, 2004; Xiong, Rao, Gao, Woldorff, & Fox, 1998). For example, Xiong et al. (1998) used positron emission tomography to monitor neural responses of nine normal subjects (all but one were right-handed) in a verb-generation task and quantified the activation in Brodmann's areas 22 and 44–47 by using an index called intensity-weighted area. They found that these subjects' asymmetry index (AI) ranged from -0.39 (right hemisphere dominated) to 1.00 (left hemisphere dominated). Six of these subjects also participated in another functional magnetic resonance imaging (fMRI) scan with the same task, and the asymmetry index also varied from 0.16 to 0.86 . There is also documented evidence of greater individual differences in language asymmetry (ranging from strong leftward lateralization to strong rightward lateralization) when processing second language than when processing native language (Dehaene et al., 1997).

Despite the accumulated evidence of individual differences in neural responses to language tasks, it is not known whether they are associated with individual differences in language ability, especially the ability to learn a new language. Such an association is plausible not only because individual differences in language abilities must be reflected, theoretically, onto the neural networks, but also because recent research has already shown neural bases of individual differences in cognitive tasks related to language. By combining functional image and training paradigms, recent studies have revealed individual differences in training effects that correspond to individual differences in brain functions (Breitenstein et al., 2005; Hashimoto & Sakai, 2004; Seger et al., 2000). For example, Hashimoto and Sakai (2004) recently showed that levels of activation in the left posterior superior temporal area were correlated with performance improvement in a task of learning to associate visual word forms with speech sounds. Similarly, Breitenstein et al. (2005) found that during an incidental associative learning task, subjects with high-level hippocampal activation at the first training session achieved better learning outcomes at the end of five training sessions.

To expand on the recent literature on neural bases of individual differences in language learning ability, we used fMRI and an intensive training program to study individual differences in cerebral asymmetry in the fusiform areas when processing a novel writing system and to use those differences to predict subsequent learning outcomes. We focused on visual word learning and the fusiform asymmetry for several reasons. First, according to a popular reading model (e.g., Warrington & Shallice, 1980), visual identification of words is the first important step toward fluent reading. Second, the fusiform

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regions are the center for high-order invariant visual object recognition (Riesenhuber & Poggio, 1999). Previous studies have shown critical involvement of fusiform areas in visual word processing in many writing systems such as English (Polk & Farah, 2002; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999), French (Cohen, Lehericy, et al., 2002; Cohen, Dehaene, et al., 2000), Japanese Kanji and Kana (Nakamura et al., 2000; Koyama, Kakigi, Hoshiyama, & Kitamura, 1998), and Chinese characters (Xue, Dong, Chen, et al., 2005; Kuo et al., 2004; Tan et al., 2001; Chee, Tan, & Thiel, 1999; also see Bolger, Perfetti, & Schneider, 2005, for a review), as well as in nonlinguistic symbols such as false fonts and consonant strings (Tagamets, Novick, Chalmers, & Friedman, 2000). In fact, this region seems to play a fundamental role, although not necessarily exclusive (see Price & Devlin, 2003, for a review), in processing abstract visual word forms (Cohen & Dehaene, 2004). Finally, we chose to study cerebral asymmetry because of the asymmetrical nature of language processing and the documented individual variations as mentioned above.

Twelve native Chinese-speaking college students who had no previous experiences with the Korean writing system were recruited to undergo a 2-week training to learn 120 Korean Hangul characters. Subjects were scanned before and after training. During the scan sessions, subjects viewed, in a block design, 64 Chinese and 64 Korean characters that were matched in complexity (e.g., number of strokes; see Methods for details).

METHODS

Subjects

Subjects were 12 Chinese college students (6 men and 6 women, 18–21 years of age) who had not learned any Korean language. They were strongly right-handed as judged by the Snyder and Harris's handedness inventory (Snyder & Harris, 1993). They gave written consent according to the guidelines set by the MRI Center at the Beijing 306 Hospital.

Training

Subjects underwent a 2-week training program on the visual forms of the 120 Korean characters. These Korean Hangul characters were carefully selected to match 120 high-frequency Chinese characters in terms of visual complexity (i.e., number of strokes and units as defined by Chen, Allport, & Marshall, 1996). For 5 days a week and 2 hr per day, subjects were required to finish six blocks of delayed matching task and one writing task. During each block of delayed matching task, 80 pairs (40 matched pairs that had the same character and 40 unmatched pairs that had two different characters) were randomly constructed using the whole set of 120 Hangul characters. Three different fonts were used in

this training: gulim [A], gungsuh [B], and a handwritten font written by a research assistant [C]. This allowed for six ways to present the pairs of characters: AA, BB, CC, AB/BA, BC/CB, and AC/CA. There was one training block for each kind of font pair. Subjects were asked to judge whether the pair of characters presented had the same or different characters. Positive (i.e., a high-pitch “beep”) or negative feedback (i.e., a low-pitch “beep”) was given for each trial. For the writing task, subjects were asked to copy all 120 characters three times. These manipulations would help subjects to acquire the abstract visual form of these characters. With the progress of the training, the difficulty in the delayed matching task was gradually increased by decreasing the presentation duration (from 1 sec to 250 msec) while increasing the between-stimulus interval (from 1 to 3 sec).

Behavioral Tasks

Subjects were tested before and after the 2-week training. We adopted a simultaneously presented same-different judgment task (Henderson, 1974; Eichelman, 1970) to examine the effect of training on behavioral performance. For this task, subjects were asked to decide whether the paired characters were identical or different. This task was able to reflect the efficiency in visual analysis and recognition (Henderson, 1974). All 120 Chinese and Korean characters were used in the tests. For each language, 40 matched pairs and 40 unmatched pairs were carefully (not randomly as during training) constructed so that the two characters for each pair matched in visual complexity as mentioned above (i.e., number of units and spatial arrangements). Furthermore, Chinese pairs matched Korean pairs in visual complexity and similarity as well. The Korean test was presented only in the most standard typeface (the Gulim font). The Chinese test was presented in the standard Song font. During the test, a pair of stimuli appeared in the central positions on the screen and would stay on until subjects responded. Subjects pressed the right “Shift” key on the keyboard to indicate a “yes” response, and pressed the left Shift key to indicate a “no” response. If no responses were made in 3 sec after stimulus presentation, the stimulus would disappear. The next stimulus would begin after an interval of 1 sec. Prior to the main experiment, there were 10 pairs of practice stimuli for each task.

fMRI Paradigm and Parameters

Sixty-four Chinese characters and 64 Korean characters were selected for the passive-viewing task during imaging scans. Block design was used in this experiment. Four Chinese blocks and four Korean blocks were arranged into one scanning session, and the sequence of the two types of blocks was counterbalanced. Each experimental block (24 sec) was preceded by an 18-sec

control block (fixation). A 15-sec fixation at the beginning of the scanning session allows for stability in magnetization, and these images were excluded from analyses. Through a mirror attached to the head coil, subjects viewed stimuli that were projected on a translucent screen. The stimuli were presented in black on a white background in the center of the screen for 750 msec, followed by a blank of 750 msec.

The scans were performed at the MRI Center of the Beijing 306 Hospital on a 2.0-T GE/Elscint Prestige whole-body MRI scanner (Elscint Ltd., Haifa, Israel) with a standard head coil. Single-shot T2*-weighted gradient-echo, EPI sequence was used for the functional imaging acquisition with the following parameters: TR/TE/ θ = 3000 msec/60 msec/90°, FOV = 375 × 210 mm, matrix = 128 × 72, and slice thickness = 6 mm. Eighteen contiguous axial slices parallel to the AC–PC line were obtained to cover the whole cerebrum and partial cerebellum. The anatomical MRI was acquired by using a T1-weighted, 3-D gradient-echo pulse sequence. The parameters for this sequence were TR/TE/ θ = 25 msec/6 msec/28°, FOV = 220 × 220 mm, matrix = 220 × 220, and slice thickness = 2 mm. Eighty-nine axial slices parallel to the AC–PC line were acquired to provide a high resolution of the anatomy of the whole brain.

Analysis of Imaging Data

Image preprocessing and statistical analyses were performed with the Statistical Parametric Mapping (SPM2, Wellcome Department of Cognitive Neurology, London, UK), which is implemented in Matlab (Mathworks Inc. Sherborn, MA). Functional images were realigned, unwarped, normalized to Montreal Neurological Institute (MNI) template (Friston, Ashburner, et al., 1995), and smoothed with 8 mm full-width half-maximum Gaussian filter. General linear model was used to estimate the condition effect for individual participants (Friston, Holmes, et al., 1995). Boxcar convolved with hemodynamic response function (HRF) was selected as reference function. Individual results were acquired by defining proper effects of interests for each subject with the relevant parameter estimates. The threshold for significant activation was $p < .05$ (multiple-comparison corrected). The group-averaged effects were computed with a random-effects model. For group results, clusters with more than 10 voxels (3 × 3 × 3 mm) activated above a threshold of $p < .001$ (uncorrected) were considered as significant.

Region of Interest Selection and Quantification of Asymmetry

To provide an unbiased examination of the training effect in the fusiform cortex, we decided to use a method that is able to define the functional region of interest (ROI) for each subject in each test session. In doing so, anatomical boundary including the left and

right fusiform cortex was used to refine the search for activation. We used an index called “intensity-weighted area” (Xiong et al., 1998), which was defined as the sum of the intensity of voxels that survived the given threshold ($p < .05$, corrected multiple comparison in this study). This could comprehensively characterize activation in terms of both spatial extent and intensity. To determine the asymmetric index (AI) in this area, we used the following formula: $AI = (L - R) / (L + R) \times 100\%$, where L and R represent the intensity-weighted volumes in the left and right ROI, respectively. A positive AI indicates left-hemispheric lateralization and a negative number indicates right-hemispheric lateralization; a number close to zero (i.e., $-0.1 \leq AI \leq 0.1$) indicates a bilateral activation.

RESULTS

Behavioral Results

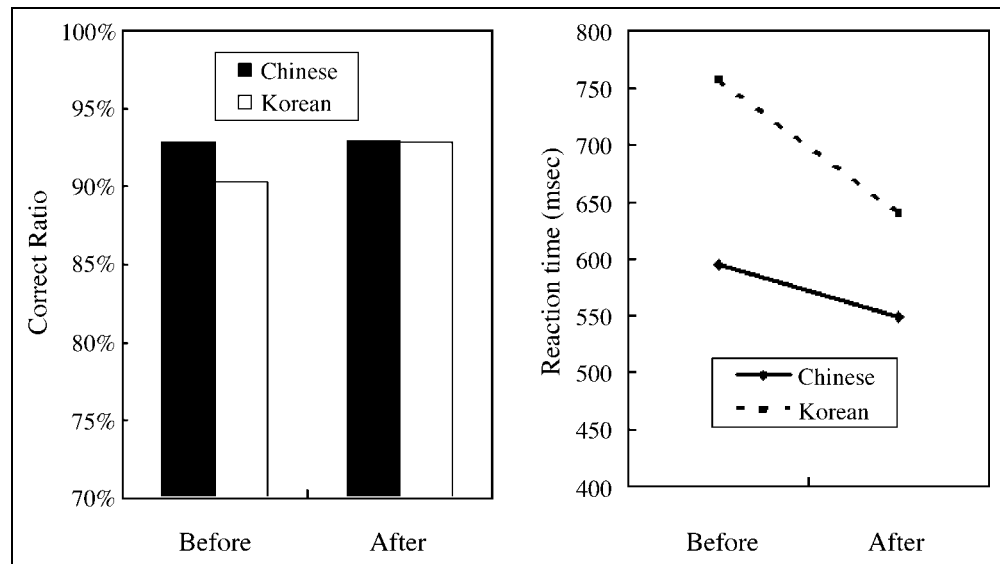
Figure 1 shows significant improvement in behavioral performance (measured with a same–different judgment test) as a result of training: a reduction of 117 msec in reaction time (RT), $t(11) = 5.92$, $p < .001$, and a 3-percentage-point increase in accuracy, $t(11) = 2.64$, $p = .02$. It is worth noting that the posttraining behavioral performance was close to that for the same task in their native Chinese language (an accuracy rate of 93% for Korean characters vs. 93% for Chinese characters and an RT of 640 msec for Korean characters vs. 595 msec for the Chinese characters [initial test]). To evaluate the possibility that the increased behavioral performance for Korean characters was merely a general increase in motor response (or routine), we performed a language by training ANOVA. A significant language by training interaction, $F(1,11) = 49.43$, $p < .001$, indicated that the change in behavioral performance on the Korean task was indeed a training effect.

Imaging Results

Overall Activation Pattern When Viewing a New Writing System

Compared to fixation, both Chinese and Korean characters elicited strong activations in a largely common network of brain regions related to language processing, namely, in the bilateral ventral visual stream including the middle/inferior occipital gyrus (BA 18), the middle occipital gyrus (BA 39/17), the fusiform gyrus (BA 19/37), left inferior parietal lobule (BA 40), left precentral cortex (BA 6), and the bilateral inferior frontal cortex (BA 45/44/47; Figure 2, Table 1). The overlapping activation in these regions is consistent with previous findings that suggested a common network for native and novel visual strings (Tagamets et al., 2000). The left inferior parietal lobule showed additional activation for Korean Hangul characters, perhaps due to the extensive visual–spatial

Figure 1. Behavioral performance on the same-different judgment tasks of Chinese and Korean Hangul characters: correct ratio (left) and response time (right).



analysis imposed by the novel/unfamiliar characters (Tagamets et al., 2000). Finally, the present study also revealed additional bilateral insula (BA 13) activation for Korean characters. The insula, considered as part of the paralimbic cortex, has connections with the sensorimotor cortices and the inferior parietal cortex and thus might play a role in the attentional aspects of human behavior (Manes, Paradiso, Springer, Lamberty, & Robinson, 1999).

Fusiform Activation and the Effect of Training

Focusing on the fusiform areas, we found that before training, Korean characters elicited greater activation than the Chinese characters in both hemispheres (main effect of language: $F = 4.75$, $p = .052$; language by hemisphere interaction: $F = .217$, ns ; Figure 3). After

training, there was a significant reduction in brain activation for the Korean task in both hemispheres (main effect of training: $F = 7.983$, $p < .05$; training by hemisphere interaction: $F = .334$, ns). For the Chinese task, the levels of activations showed little change from pretraining to posttraining scans in either hemisphere (main effect of training: $F = .005$, $p = .943$).

Cerebral Asymmetry in Fusiform Regions and Its Stability

We quantified the activation for each subject in the bilateral fusiform cortex and calculated the AI for each subject in this region. Results from the pretraining scans showed consistent leftward lateralization (ranging from .11 to .85) in the fusiform cortex when viewing Chinese characters, as found in previous studies (e.g., Xue,

Figure 2. Group-averaged t map for Chinese characters (top) and Korean characters (bottom) relative to the fixation obtained from the pretraining scans were overlaid onto a standard MNI template provided by SPM2. Clusters that survived an uncorrected $p < .001$ ($t = 4.02$) with spatial extent ≥ 10 were considered as statistically significant.

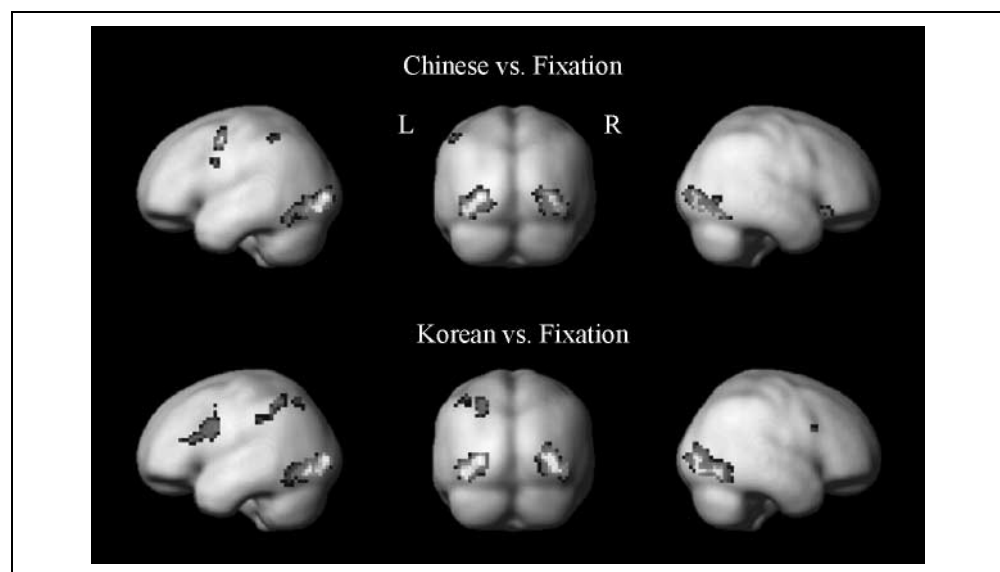


Table 1. Foci of Activations in Chinese and Korean Passive Viewing Tasks

Brain Region	BA	Chinese vs. Fixation				Korean vs. Fixation			
		x	y	z	Z	x	y	z	Z
L inferior frontal gyrus	45	-48	18	10	3.17	-39	24	15	4.25
R inferior frontal gyrus	47	42	23	-11	3.87	-	-	-	-
R inferior frontal gyrus	44	-	-	-	-	42	13	24	3.96
L precentral gyrus	6	-45	1	28	3.84	-42	1	25	4.96
		-39	-1	47	5.00	-30	2	41	3.97
L insula	13	-	-	-	-	-39	24	15	4.25
R insula	13	-	-	-	-	36	7	19	3.49
L inferior parietal lobule	40	-53	-41	49	3.56	-36	-47	44	4.49
L superior parietal lobule	7	-	-	-	-	-24	-65	45	3.82
L fusiform gyrus	37	-39	-59	-12	4.65	-36	-53	-12	4.22
L fusiform gyrus	19	-39	-73	-9	4.69	-42	-73	-6	4.98
R fusiform gyrus	37	39	-59	-12	3.35	39	-56	-10	4.03
L middle occipital gyrus	37/19	-36	-82	-3	4.87	-39	-64	-4	4.67
R middle occipital gyrus	37/19	42	-76	-6	4.56	48	-64	-4	4.73
L middle/inferior occipital gyrus	18	-27	-87	4	5.38	-27	-90	5	4.94
R middle/inferior occipital gyrus	18	30	-87	-1	4.50	30	-85	-3	5.05

BA = Brodmann's area; L = left; R = right.

Dong, Chen, et al., 2005), but great individual variations in AI (from $-.47$ to $.94$) when viewing the new Hangeul characters, in accord with previous findings of second-language processing (Dehaene et al., 1997; Figure 4A).

Figure 4B shows the comparison between pre- and posttraining asymmetry indices when processing Korean characters. Clearly, there was a high stability in laterality. Pearson correlation coefficient between the two indices was $.778$, $p = .002$. This indicated that 2 weeks of intensive visual form training had little effect on the laterality of processing a new (or a newly learned) writing system. If anything, there appears to be a trend for polarization in the asymmetry index: The initially

leftward individuals became slightly more leftward, whereas the initially rightward individuals became more rightward after training.

Cerebral Asymmetry and Learning Outcome

Finally, we examined the correlation between these stable individual differences and behavioral performance. Due to the high accuracy rate, only RT data could be used to explore this question. First, Figure 5A and B shows the scatter plots between AI from pre- and posttraining scans and the RT on the matching test

Figure 3. Training-induced change in the fusiform cortex. (Left and Right) Change in terms of intensity-weighted area in the left and right fusiform, respectively. (Middle) Schematic activation in fusiform regions while processing Korean characters.

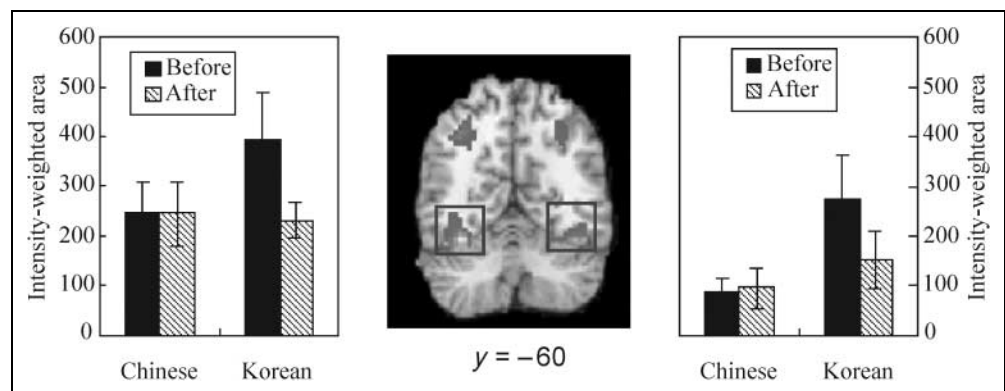
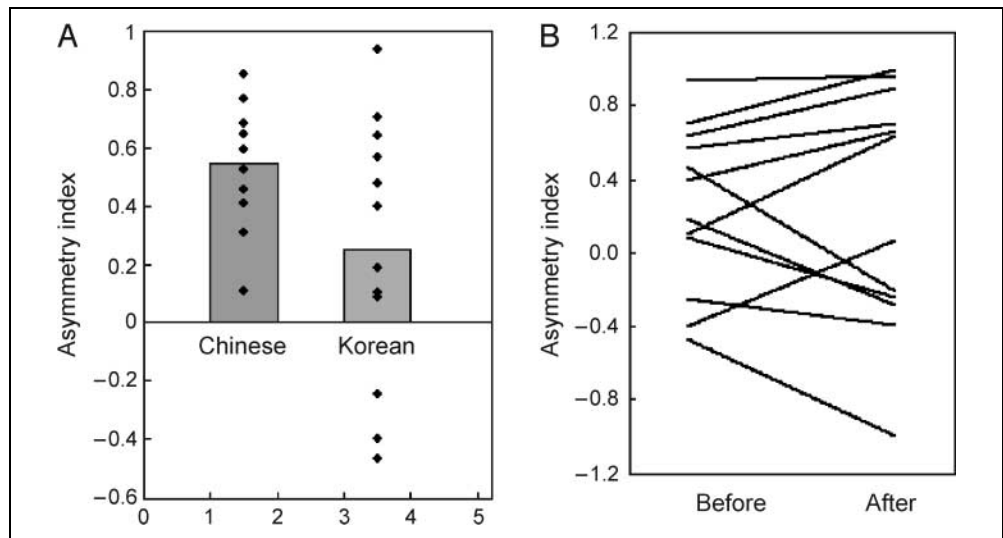


Figure 4. Asymmetry indices (AIs) in the fusiform regions. (A) AI when processing Chinese and Korean characters from the pretraining scans. Dots represent individual data and height of the bar represents the mean value. Please note that there were only eleven individuals for the Chinese task because one subject did not show activation in either left or right fusiform beyond the threshold of $p < .05$ (corrected). (B) Individual asymmetry indices before and after training in the fusiform cortex when processing Korean characters.



administered after the training. It is evident that leftward laterality was associated with a better performance on the posttraining test. In order to evaluate the contribution of cerebral asymmetry to the change in performance (not just ultimate performance), we conducted a regression analysis that controlled for pretraining performance. Results showed that pretraining asymmetry strongly predicted posttraining performance after controlling for pretraining performance, $\beta = -.793$, $t = -4.47$, $p = .002$, total $R^2 = .75$. In other words, the more left-lateralized individuals showed a greater improvement relative to their right-lateralized counterparts. It is also worth noting that the significant correlation between posttraining AI and the posttraining behavioral performance as shown in Figure 5B was no longer significant ($r = .332$, $p = .317$) when we controlled for pretraining AI. That means the apparent

association between posttraining performance and posttraining AI was mainly due to the stability of AI.

DISCUSSION

The present study aimed to explore individual differences in cerebral asymmetry when processing a novel writing system and their association with subsequent learning outcomes. Consistent with previous observations (Tzourio-Mazoyer et al., 2004; Xiong et al., 1998), the present study revealed significant individual differences in cerebral asymmetry in fusiform regions when processing native writing (i.e., Chinese). Moreover, we found that individual differences in AI were more pronounced when processing a novel writing (i.e., Korean Hangul), which seemed to corroborate the Dehaene et al. (1997) finding of greater individual differences in

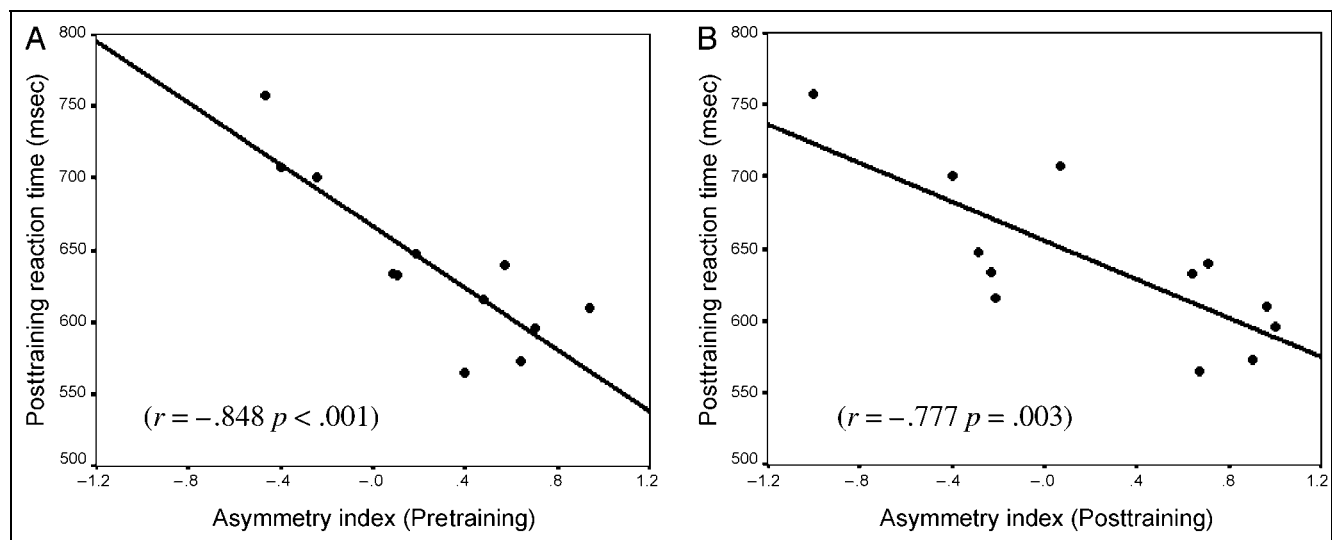


Figure 5. Scatter plots and correlation coefficients between the AI and the posttraining behavioral performance for Korean characters: (A) between pretraining AI and posttraining performance, (B) between posttraining AI and posttraining performance.

second-language processing. One explanation of these results is that individual differences in neural responses might be amplified with increasing cognitive demand placed by a new or newly learned language (Xue, Dong, Zhen, & Chen, 2004; Hasegawa, Carpenter, & Just, 2002; Chee, Hon, Lee, & Soon, 2001). In response to this increased cognitive demand, it is possible that different individuals may use different types of neural compensation. Some may recruit the homologous area in the right hemisphere for the new tasks (thus, bilaterality), whereas others may recruit surrounding brain areas (more leftward laterality), and still others may even rely on the right hemisphere (thus, rightward laterality).

More importantly, our results revealed an association between cerebral asymmetry and the posttraining behavioral performance, a finding that should have important implications for our understanding of the neural mechanisms of learning. In line with the Breitenstein et al. (2005) study, the present study confirms the usefulness of neurobiological measurement in predicting the outcomes of language learning. Specifically, our results showed that the quantitative and/or qualitative difference in the reliance on hemispheric resource may be a key indicator of whether someone is a good or poor language learner. Left-hemisphere-dominant individuals appear to have an advantage in learning, at least in the task used in the present study.

Our study also has an important implication for future research on brain plasticity. By now, many studies have correlated behavioral training effects with neural response patterns after the training (e.g., Hashimoto & Sakai, 2004; Seger et al., 2000). Such a correlation has been interpreted as evidence of brain plasticity (i.e., individuals with more behavioral changes showed greater neural changes). Because individual differences in neural responses in these studies were observed after the training or in the middle of the training, the significant correlations between behavioral change and patterns of neural responses are subject to two different interpretations. The first interpretation, favored by the authors of the original studies, is that different learning induces different degrees of neurological changes (i.e., brain plasticity). In other words, those individuals who learned more showed greater neurological “changes” (assuming all individuals had the same initial neural responses) than those who learned less. Another possible explanation, as shown by the present study, is that individual differences in responses “predated” and thus likely effected the behavioral change. Brain plasticity hypothesis cannot explain the significant association between pretraining scans and posttraining performance. It should be pointed out, however, that the individual differences perspective does not mean that there is no training-induced plasticity. In both our study and the previous studies, the mean level of activation changed dramatically as a result of training, a clear indication of brain plasticity. The individual differences

perspective only states that within the large context of brain plasticity, there are patterns of neural responses (“neural traits”) that are relatively stable over time and vary systematically across individuals.

Much more research is needed to understand the nature of the association between functional asymmetry and learning efficiency. Here, we would like to propose several lines of future research. First, future research should explore the mechanisms for the left hemisphere’s efficiency in learning a new writing system. It is possible that due to its dominant role in native language processing, the left hemisphere is particularly suitable for learning new languages. Specifically, as the left fusiform has long been involved in the processing of visual words from an early age of reading acquisition (Xue, Dong, Chen, et al., 2005; Gaillard et al., 2001), neurons in this area might be tuned to be very efficient in processing visual word form. Following this idea, Cohen and his colleagues have labeled the left mid-fusiform as visual word form area (VWFA; Cohen & Dehaene, 2004; McCandliss, Dehaene, & Cohen, 2003; Cohen, Lehericy, et al., 2002; Cohen, Dehaene, et al., 2000). To support this speculation of efficient VWFA for learning a new language, we will need direct evidence of the superiority of left fusiform over the right fusiform in visual word processing and direct evidence of a transfer between native-language processing and second-language learning.

More broadly, future research needs to examine the functional specification of the two hemispheres. It has been proposed that the left and right hemispheres might be, respectively, specialized for processing high-frequency versus low-frequency information (Kitterle & Selig, 1991), part versus whole (Robertson & Lamb, 1991), feature versus holistic information (Grill-Spector, 2001), and abstract identity versus form-specific information of visual objects (Marsolek, Kosslyn, & Squire, 1992). To extend our findings to the general functional specification perspective, we might hypothesize that depending on the task, different types of cerebral asymmetry will be associated with better learning outcomes (e.g., leftward lateralization predicts better learning of high-frequency information, whereas rightward lateralization predicts better learning of low-frequency information).

Finally, future research should also explore the origins of individual differences and examine whether some general factors might account for the association between cerebral asymmetry and learning efficiency. For example, studies combining structural and functional imaging have revealed connections between anatomical asymmetry and functional lateralization (e.g., Foundas, Leonard, Gilmore, Fennell, & Heilman, 1994, 1996). Other studies found relations between the cortical surface of the left hemisphere and left activations, but did not find evidence for a connection between anatomical asymmetries and hemispheric specialization for

language (Tzourio, Nkanga-Ngila, & Mazoyer, 1998). More research is needed to explore the sources of individual differences in cerebral asymmetry by examining various levels of brain structures and functions.

In sum, the present study revealed that there were significant and stable individual differences in the hemispheric involvement in processing a novel writing, and that those individual differences strongly predicted subsequent learning outcome. If future research replicates these findings and finds sources of these individual differences (e.g., differences in early language training), this line of research will provide insights to brain-based training and education (e.g., new ways to facilitate the involvement of the left fusiform in language learning).

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The data reported in this experiment have been deposited with the fMRI Data Center (www.fmridc.org). The accession number is 2-2006-121GX.

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