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Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 33(33)

ISSN

1069-7977

Authors

Lam, Sze-Man
Hsiao, Janet Hui-wen

Publication Date

2011

Bilinguals Have Different Hemispheric Lateralization in Visual Word Processing from Monolinguals

Sze-Man Lam (fannylam@hku.hk)
Janet Hui-wen Hsiao (jhsiao@hku.hk)
Department of Psychology, University of Hong Kong
Pokfulam Road, Hong Kong

Abstract

Previous bilingual studies showed reduced hemispheric asymmetry in visual tasks such as face perception in bilinguals compared with monolinguals, which suggested that hemispheric asymmetry in visual tasks could be modulated by experience in reading one or two languages. Here we examined whether difference in hemispheric asymmetry in visual tasks can also be observed in bilinguals who have different language backgrounds. We compared the behavior of three language groups in a tachistoscopic English word sequential matching task: English monolinguals (or alphabetic monolinguals, A-Ms), bilinguals with an alphabetic language L1 and English L2 (alphabetic-alphabetic bilinguals, AA-Bs), and bilinguals with a logographic language (Chinese) L1 and English L2 (logographic-alphabetic bilinguals, LA-Bs). The results showed that AA-Bs had a stronger right visual field/ left hemispheric (LH) advantage than A-Ms and LA-Bs, suggesting that different language learning experiences can influence how visual words are processed in the brain. In addition, we showed that this effect could be accounted for by a computational model that implements a theory of hemispheric asymmetry in perception (i.e. the Double Filtering by Frequency theory, Ivry & Robertson, 1998); the modeling data suggested that this difference may be due to both the difference in participants' vocabulary size and the difference in word-to-sound mapping between alphabetic and logographic languages.

Keywords: Hemispheric asymmetry; bilingualism; visual word recognition; computational modeling.

Introduction

Researchers have found different functional dominance between the two hemispheres. One of the most salient functional differences is the superiority of the left and right hemisphere (LH and RH) in language processing, especially in phonology processing (Corina, Vaid, & Bellugi, 1992), and in visuospatial processing and face processing (Kanwisher, McDermott, & Chun, 1997) respectively.

Despite the converging evidences showing the RH superiority in specific tasks such as face recognition and visuospatial tasks, there have been studies showing reduced lateralization in these well-known RH tasks in bilinguals compared with monolinguals. Back in the 1980s, Sewell and Panou (1983) observed the typical right visual field (RVF)/ LH advantage in accuracy in an English word naming task in both bilinguals and monolinguals; in contrast, the typical left visual field (LVF)/ RH advantage in a spatial dot localization task was only found in monolinguals but not in bilinguals. In this task, a 4x5 grid with a dot in one of the boxes was shown unilaterally, and participants were required to report the location of the dot. Therefore, Sewell and Panou's results (1983) suggested that the processing of some visual tasks such as spatial dot localization may be influenced by participants' language experiences. About 20 years later, Hausmann et al. (2004) examined performance of bilinguals and monolinguals in visual tasks and found consistent results. They showed that in the accuracy data of both groups, a typical RVF/LH advantage was found in a sequential word-matching task whereas a typical LVF/RH advantage was found in a face detection task; however, the respond time data revealed a significant LVF/RH advantage in the face detection task only in monolinguals but not bilinguals. This result suggested that the RH visual processing abilities may be affected by language experience.

The above results seemed to suggest that hemispheric asymmetry in RH dominant visual tasks such as face perception and spatial localization could be affected by language experience, but not for LH dominant visual tasks such as visual word recognition. However, some difference between the bilinguals and monolinguals was observed in Sewell and Panou's study (1983). In their word naming task, words were presented unilaterally and the participants were required to report the word they perceived; the display time was 20ms and 40ms for monolinguals and bilinguals respectively. The authors selected these display times where the two groups made approximately the same number of errors. This suggested that bilinguals might process the words differently compared with monolinguals. In addition, in the word sequential matching task in which Hausmann, et al. (2004) did not find performance difference between bilinguals and monolinguals, a centrally presented word was followed by a unilaterally displayed word; the exposure time was 175ms for both groups. As the same display time was used for both groups and performance level between groups was not controlled, the results from the word sequential matching task of Hausmann, et al. (2004) might not completely reflect the difference between bilinguals and monolinguals in visual word processing. Therefore, in this study, we aim to control for the performance level in the sequential word matching task employed by Hausmann et al. (2004) for investigating the impact of language experience on hemispheric asymmetry in visual word recognition.

Moreover, as all the previous studies investigated only the population of alphabetic language users, here we aim to investigate hemispheric asymmetry in visual word recognition in the following three groups of people with different language experiences: (1) alphabetic monolinguals (A-Ms), who know only one alphabetic language; (2)

alphabetic-alphabetic bilinguals (AA-Bs), who are proficient in two alphabetic languages; and (3) logographic-alphabetic bilinguals (LA-Bs), who acquire a logographic language (e.g. Chinese) and an alphabetic language with high proficiency in both. We believe that an investigation on the behavioral difference between AA-Bs and LA-Bs will provide a broader view on how different language experiences modulate hemispheric asymmetry in visual word recognition. We describe the differences between alphabetic and logographic languages below.

In alphabetic language processing, functional MRI studies revealed a specific region in the LH (i.e. the visual word form area) that responds to words selectively (McCandliss, Cohen, & Dehaene, 2003); some researchers (Maurer & McCandliss, 2007) suggested that the observed LH lateralization in alphabetic language processing is due to the application of grapheme-phoneme conversion (GPC) rules during learning to read. Behavioral studies also found a RVF/LH advantage in reading words in alphabetic languages in tachistoscopic recognition (Bryden & Rainey, 1963). In short, the superiority of the LH in processing alphabetic languages has been consistently reported.

In contrast to alphabetic languages, the relationship between written and spoken logographic languages, such as Chinese, is more opaque due to its morphosyllabic features. Moreover, stroke patterns in Chinese characters do not map to phonemes in the pronunciation, so GPC rules in alphabetic languages do not apply to Chinese reading. Functional MRI studies (Tan et al., 2001; Tan et al., 2000) showed more activation in the visual areas in the RH than the LH in reading Chinese characters, and this effect has been argued to be due to elaborated visual analysis required for processing spatial information and locations of strokes. In behavioral studies, a LVF/RH advantage was observed in tachistoscopic recognition of Chinese characters (Tzeng, Hung, Cotton, & Wang, 1979); in a recent study, Hsiao and Cottrell (2009) showed a left side bias effect in Chinese readers but not in non-Chinese readers in a Chinese character perception task, suggesting more RH involvement in Chinese characters recognition. In sum, the superiority of the RH in processing the orthography of logographic Chinese, a logographic language, has been consistently reported.

Due to the dramatic differences in orthographic processing and hemispheric lateralization between alphabetic and logographic languages, we predict that in visual word recognition, (1) as alphabetic reading involves more LH processing, and AA-Bs have acquired one more alphabetic language than A-Ms, AA-Bs may have a stronger LH lateralization than A-Ms; and (2) although both AA-Bs and LA-Bs acquired two languages, logographic reading involves more RH processing, and thus AA-Bs may show a stronger LH lateralization than LA-Bs.

Behavioral Study

We examined hemispheric asymmetry in visual word recognition in three groups of participants with different language backgrounds, namely, A-Ms, AA-Bs, and LA-Bs, using a divided visual field word sequential matching task modified from Hausmann, et al. (2004).

Participants

66 participants were recruited; all were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971), and had normal or corrected to normal vision. Participants were undergraduate or postgraduate students at the University of Hong Kong and were divided into three groups of equal size (n=22) according to their language background: English monolinguals (A-Ms), bilinguals with an alphabetic language L1 and English L2 (AA-Bs), and bilinguals with Chinese L1 and English L2 (LA-Bs). The A-Ms spoke English as their L1 and could not fluently use any other languages. The AA-Bs learnt a non-English, west European alphabetic language as their L1 (i.e., French, Spanish, Dutch, German or Italian), and English as their L2 during schooling; they were proficient in both their L1 and English. Both A-Ms and AA-Bs had none or very limited knowledge about logographic scripts such as Chinese characters. The LA-Bs were local Hong Kong students who learnt Chinese as their L1 and English as an L2 since kindergarten in formal education; they were proficient in both Chinese and English. Average age of acquisition of English was 3.3 for LA-Bs and 7.4 for AA-Bs.

Stimuli & Procedures

We used an English word sequential matching task to measure hemispheric lateralization in English word processing in the three groups. A hundred pairs of English words were selected as the test stimuli from the SUBTLEX$_{US}$ corpus (Brysbaert & New, 2009). In each pair, the two words had the same number of letters and the same initial and final letters, and were matched in word frequency. The length of the word stimuli ranged from four to seven and the average frequency of the word stimuli was 407.57 per million words in the SUBTLEX$_{US}$ corpus.

The task consisted of a pre-test and a test. In the pre-test, the staircase method was employed to determine a perceptual threshold for each participant in the word matching task, in which the participant achieved reliably 80% accuracy. A 1-up 3-down staircase rule was applied (Hartmann, 2004). That is, for every three consecutive correct responds, the display time was decreased by one refresh rate, and every single incorrect response made the display time increased by one refresh rate. Three staircases were run in each pre-test, and each run proceeded until eight turnarounds had occurred. Only the third to the eighth turnarounds were averaged and used as the estimate of the threshold. The display time for the English words in the subsequent sequential matching task was then calculated by averaging the estimated thresholds of the three runs[1]. The pre-test followed a similar procedure as the test except all the stimuli were presented at the center of

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[1] Note that average threshold for A-Ms (53ms) were slightly lower than LA-Bs (59ms) and AA-Bs (62ms).

the screen. The stimuli used in the pre-test were not used again in the test.

There were 100 trials in the test. In each trial, after a 1000ms central fixation, the first stimulus was presented either in the LVF or RVF, at about 1.5^{o} to 5^{o} of visual angle away from the centre (thus the size of the stimulus was about 3.5^{o}), for the display time obtained in the pre-test. The second stimulus was then presented at the center of the screen after another 1000ms central fixation. There were equal numbers of stimuli presented in the two visual fields. The presentation order and condition (LVF or RVF) was randomized. Participants were asked to judge whether the two stimuli were the same by pressing corresponding keys on the keyboard.

Results

Here we define the variable hemisphere lateralization as the performance difference between the LVF/RH and the RVF/LH conditions in terms of accuracy; therefore, positive and negative indices reflect RH and LH lateralization respectively. One-sample t-test against zero and ANalysis Of VAriance (ANOVA) were used for the analysis. Hemispheric lateralization was the dependent variable and language background was the independent variable.

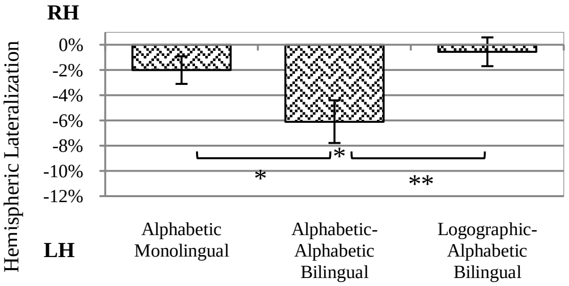

Figure 1: Results from the behavioral experiment. (* $p < .05$, ** $p < .01$). Error bars show one standard error.

The results from a one-sample t-test against zero showed a significant LH lateralization among all the participants ($t(65) = -3.538$, $p = .001$). For individual groups, a significant LH lateralization was found only in AA-Bs ($t(21) = -3.598$, $p = .002$), while A-Ms showed a tendency of a LH lateralization ($t(21) = -1.830$, $p = .082$) and LA-Bs did not exhibit any significant LH lateralization ($t(21) = -.478$, n.s.). ANOVA also showed a significant effect of language background on hemispheric lateralization ($F(2, 63) = 4.625$, $p = .013$); post hoc analysis showed that the LH lateralization was significantly stronger in AA-Bs than the other two groups (independent t-test, A-Ms: $t(42) = -2.030$, $p = .049$; LA-Bs: t(42) = -2.717, p = .01).

These results are consistent with our predictions that in the English word sequential matching task, AA-Bs have more LH lateralization than both A-Ms and LA-Bs. Thus, it suggests that hemispheric lateralization in visual word recognition may be affected by language experience and also the orthographic processing of the languages.

Computational Modeling

Here we aimed to account for the behavioral results through computational modeling. We hypothesized that the hemispheric lateralization difference in English word processing among the three groups may be due to two factors: (1) bilinguals have a larger vocabulary size, and (2) reading in alphabetic and logographic languages involve different word-to-sound mappings. We applied the intermediate convergence model proposed by Hsiao, Shieh, and Cottrell (2008) to model bilingual visual word recognition. Hsiao et al. (2008) showed that this model was able to account for the left-side bias effect in face perception observed in human data (Brady, Campbell, & Flaherty, 2005). The model incorporates several known observations about visual anatomy and neural computation and implements a theory of hemispheric asymmetry in perception, Double Filtering by Frequency (DFF, Ivry & Robertson, 1998), but does not assume a LH localized language center. The DFF theory posits that visual information is captured by frequency-based representation at multiple scales, and the frequency information is filtered at two stages; in the first stage, a task-relevant frequency range is selected through attention processes; and at the second stage, asymmetric filtering processing is applied to the two hemispheres: The LH amplifies high spatial frequency (HSF) information, while the RH amplifies low spatial frequency (LSF) information. We describe our modeling details below.

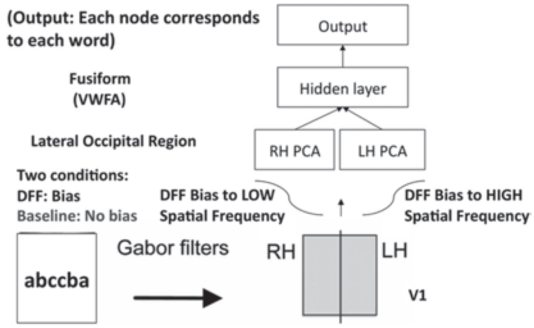

Figure 2: Hsiao et al.'s hemispheric processing model (2008)

In the model, each input image (35x60 pixels) was first filtered with a rigid grid (5x10) of overlapping 2-D Gabor filters (Daugman, 1986) at five scales and eight orientations. Gabor filters were used to simulate neural responses of complex cells in the early visual system (Lades et al., 1993), and the frequency range represented the task-relevant frequency range in DFF theory, as the five scales corresponded to 2 to 32 (i.e., 2^1 to 2^5) cycles per word whereas our image height was 35 pixels. After the Gabor filters, each input image was transformed into a vector of size 2000 (5x10 sample points x 5 scales x 8 orientations). A base-line condition and a biased condition were then created. The second stage of the DFF theory was only applied to the biased condition, in which the Gabor responses of the left and right half of the word were biased to low and high spatial frequencies respectively by applying a sigmoidal weighting function. In contrast, in the base-line condition, equal weights were given to the Gabor responses of different scales. The Principal Component Analysis (PCA), a biological plausible linear compression technique (Sanger, 1989), was then applied to the Gabor representations of the left and right half-words separately to compress each representation into a 50-element representation (i.e., 100 elements in total). This PCA representation was then used as the input to a two layer neural network (See Hsiao et al., 2008, for more simulation details).

Our model was trained to recognize the input images until the performance on the training set reached 100% accuracy. The training algorithm used was gradient descent with an adaptive learning rate. To test hemispheric asymmetry effects, we used left or right half damaged inputs, which were generated by setting one half of the PCA representation to zero. When mapping damaged inputs to their corresponding outputs, only the representation from one of the visual fields was informative in recognition. Thus, in the biased condition, a right-damaged word carried only LSF/RH information and a left-damaged word carried only HSF/LH information. The RH (LSF) lateralization effect was then measured as the accuracy difference between recognizing a right-damaged word and a left-damaged word as the original word. The model was run 40 times in each condition in the analysis.

We created artificial lexicons for the current examination. Each word consisted of three letters. The task of the model was to map each word input to its pronunciation with a consonant-vowel-consonant (CVC) structure. Each lexicon consisted of an alphabet of size 13; eight letters were randomly assigned as consonants and the rest five letters as vowels in the pronunciation. Eight different fonts of the words were used as input images; four of them were used as the training set and the other four as the testing set. The output layer was divided into three parts; each part corresponded to a position in the CVC structure, and each node corresponded to a phoneme in that position. To counterbalance the information available in the left and right side of the input images, in each lexicon, the frequency of each letter in the first and third position was kept equal; mirror images were used in half of the simulation runs.

In order to compare with the behavioral data, we built three models of visual word recognition with different vocabulary sizes and different orthography-to-phonology mappings to capture the behavioral differences among our three groups of participants, as describe below.

Alphabetic Reading Model (A-model) We simulated alphabetic reading by mapping each letter in a word systematically to each phoneme in the pronunciation; in addition, we examined the effect of vocabulary size by varying the number of words in the artificial lexicons from 16 to 40 (while keeping the alphabet size 13). As both our A-Ms and AA-Bs were experts in alphabetic reading, and the two languages acquired by our AA-Bs have similar alphabets (i.e. one was English and the other was a west-European language), we assumed that the behavioral difference between the two groups was mainly due to a larger vocabulary size in AA-Bs compared with A-Ms.

Logographic Reading Model (L-model) We simulated logographic reading by randomizing the mapping between each word and its pronunciation (i.e. no systematic letter-to-phoneme mapping). We also varied the vocabulary size from 16 to 40 and compared the results with the A-model to examine the difference between logographic and alphabetic reading.

Logographic-Alphabetic Model (LA-model) This model was trained to perform both alphabetic and logographic reading, so that its behavior could be compared with the LA-Bs in the behavioral data. Two alphabets were used in each simulation run, in which letters in one of the alphabet were systematically mapped to phonemes in the pronunciation, whereas in the other alphabet there was no systematic mapping. The assignment of mapping method to the two alphabets was counterbalanced among the runs. The range of the vocabulary size (half from each lexicon) also ranged from 16 to 40.

Our Hypotheses

In a recent study adopting also the intermediate convergence model (Hsiao, et al., 2008), Cheung and Hsiao (2010) demonstrated two factors that lead to more LH bias in visual word recognition: (a) visual similarity among word stimuli in the lexicon: more HSF information is required when the visual stimuli look more alike; (b) the task requirement to decompose visual stimuli into smaller parts for performing grapheme-phoneme conversion.

Here we hypothesize that (1) The LH (HSF) lateralization of the A-model will increase with vocabulary size, since the similarity of words increase with vocabulary size; this prediction is consistent with our behavioral data showing that AA-Bs exhibited a stronger LH lateralization compared with A-Ms; (2) the A-model (alphabetic reading) will show more LH (HSF) lateralization than the L-model (logographic reading), since decomposition of words is not necessary in the L-model; (3) When performing alphabetic reading, the LA-model will show less LH (HSF) lateralization than the A-model, since during learning, decomposition of words is required in only half of the times.

Results

In Figures 3 and 4, hemispheric lateralization represents the performance difference between correctly recognizing a right-damage word and a left-damaged word as the original word, in the biased condition over the base-line condition.

Vocabulary Size Both the A-model and the L-model showed an increase in LH (HSF) lateralization with increasing vocabulary size (Figure 3), and the LA-model exhibited a similar pattern as the L-model. For all three models, significant but weak positive correlations were observed between LH (HSF) lateralization and vocabulary size (A-model: $R^2 = .054$, $p < .001$; L-model: $R^2 = .070$, $p < .001$; LA-model: $R^2 = .083$, $p < .001$). These results showed that in all three models, LH (HSF) lateralization increased with vocabulary size[2].

Mapping Method Results from Figure 3 showed that the L-model (logographic reading) had a weaker LH (HSF) lateralization than the A-model (alphabetic reading) ($p < .01$, except for vocabulary size of 16).

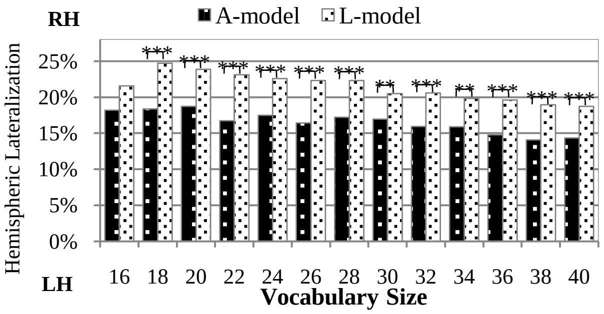

Figure 3: Results from computational modeling: hemispheric lateralization in alphabetic (A-model) and logographic reading (L-model). (* $p < .05$; ** $p < .01$; *** $p < .001$).

Model Comparison In performing alphabetic reading, the behavior of the LA-model was more similar to logographic reading in the L-model than alphabetic reading in the A-model; the LA-model showed a significantly weaker LH (HSF) lateralization than A-model (p < .01, except for vocabulary size of 16), but no significant differences from the L-model.

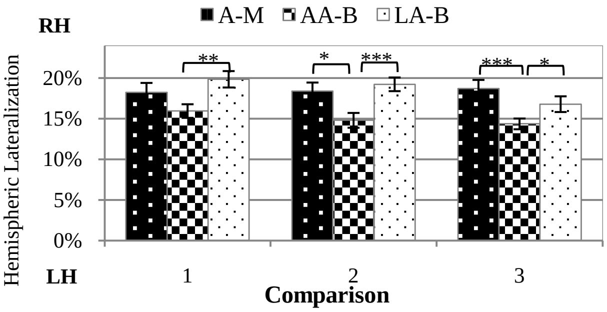

Figure 4: Results from computational modeling: hemispheric lateralization in alphabetic reading. (* $p < .05$; ** $p < .01$; *** $p < .001$). Error bars show one standard error.

Comparison with Behavioral Data The modeling data and behavioral data are compared in Figure 4. We assumed that the vocabulary size of AA-Bs' was twice of the A-Ms'. In the three comparisons, A-M data was derived from the A-model of vocabulary size of 16, 18 and 20; data for AA-Bs and LA-Bs were obtained from the A-model and the LA-model of vocabulary size of 32, 36 and 40 respectively; for the LA-model, the presented data consisted of the behavior of alphabetic reading only, to match the behavioral study.

The modeling data fit with the behavioral data well. All three comparisons exhibited a significant group difference (1: $F(2, 117) = 3.721$, $p = .027$; 2: $F(2, 117) = 6.397$, $p = .002$; 3: $F(2,117) = 5.822$, $p = .004$); post hoc showed a stronger LH (HSF) lateralization in AA-Bs than LA-Bs (1: $t(78) = -2.980$, $p = .004$; 2: $t(78) = -3.574$, $p = .001$; 3: $t(78) = -2.070$, $p = .042$). AA-Bs also showed a stronger LH (HSF) lateralization than A-Ms in comparison 2 and 3 (2: $t(78) = -2.620$, $p = .011$; 3: $t(78) = -3.531$, $p = .001$).

Discussion & Conclusion

In this study, we examined how hemispheric asymmetry in visual tasks can be modulated by language experience. Previous studies found that compared with monolinguals, bilinguals have a reduced hemispheric lateralization in RH dominant visual tasks such as face perception, but not in LH dominant visual tasks such as word naming or word matching. However, we suspected that the lateralization difference between the two groups in the LH visual tasks did not emerge because the performance level between the two groups was not matched.

Therefore, in the behavioral study, we used a perceptual threshold match in an English word sequential matching task and investigated lateralization difference among three groups of people with different language experiences: A-Ms, AA-Bs, and LA-Bs. We found a stronger LH lateralization in AA-Bs over both LA-Bs and A-Ms. We hypothesized that this effect may be due to at least two factors: (1) vocabulary size: in the study the languages acquired by A-Ms and AA-Bs used a similar alphabet, but AA-Bs learned more words overall than A-Ms; and (2) the application of GPC rules in alphabetic reading but not in logographic reading: alphabetic reading required decomposing a word into letters in order to map them to phonemes, and thus involved more LH (HSF) processing.

To verify our hypothesis, we applied the hemispheric processing model (Hsiao et al., 2008) on visual word recognition; the model implements the DFF theory (Ivry & Robertson, 1998) and does not assume any influence from the LH-lateralized language processing. The modeling data fit well with the behavioral data, explaining the above two factors: (1) vocabulary size: when the vocabulary size increases, the words in the lexicon look more similar to each other, thus more HSF information is required to distinguish words; (2) the application of GPC rules in alphabetic reading but not in logographic reading: since half of the words in LA-Bs' lexicon involve logographic mapping and thus do not require the application of GPC rules, compared

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[2] Note that the RH lateralization of the model, in contrast to the LH in the human data, was because the stimuli used (3-letter words) were simpler and the vocabulary sizes used were much smaller than the English lexicon (see Cheung & Hsiao, 2010). Here we examined relative changes in lateralization between different models rather than the absolute lateralization.

with AA-Bs, LA-Bs' behavioral might be influenced by their logographic mapping experience and thus exhibited less LH (HSF) lateralization even in alphabetic reading.

Thus, our results showed that differences in hemispheric lateralization between bilinguals and monolinguals can also be observed in LH dominant visual tasks; in addition, this effect can further be modulated by different bilingual experiences. This result suggests that our expertise domains (e.g. expertise in different languages) can influence each other, and is consistent with recent research on perceptual expertise, showing that similar brain areas are recruited for different expertise domains, and thus these domains may influence each other (e.g. Gauthier, et al., 2000).

In addition to the two factors we examined in the modeling, there are some other factors that may also account for the observed difference among the three language groups, such as the difference in word/character features between different languages, as well as the age of acquisition of the second language in the bilinguals; thus, further investigations are required to examine these factors.

In summary, here we show that hemispheric asymmetry in English word sequential matching can be modulated by bilingual language experience, and our modeling data suggested that at least two factors may account for this effect: (1) larger vocabulary size in bilinguals, and (2) the difference in word to sound mapping between alphabetic and logographic languages.

Acknowledgments

We are grateful to the HKU Seed Funding Program for Basic Research (project #10400471 to J.H. Hsiao) and the Research Grant Council of Hong Kong (project code: HKU 744509H and 745210H to J. H. Hsiao).

References

Brady, N., Campbell, M., & Flaherty, M. (2005). Perceptual asymmetries are preserved in memory for highly familiar faces of self and friend. *Brain and Cognition, 58,* 334-342.

Bryden, M. P., & Rainey, C. A. (1963). Left-right differences in tachistoscopic recognition. *Journal of Experimental Psychology, 66*, 568-571.

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods, 41*(4), 977-990.

Cheung, K. C. F., & Hsiao, J. H.-w. (2010). Visual and Task characteristics may explain hemispheric asymmetry in visual word recognition. *Proc. of the 32rd Annual Meeting of the Cognitive Science Society, Portland.*

Corina, D. P., Vaid, J., & Bellugi, U. (1992). The linguistic basis of left hemisphere specialization. *Science, 255,* 1258-1260.

Daugman, J. G. (1986). uncertainty relation for resolution in space, spatial frequency, and orientation optimized by two-dimensional visual cortical filters. *Journal of Optical Society of America A, 2*(7), 1160-1169.

Gauthier, I., Skudlarski, P., Gore, J. C., & Anderson, A. W. (2000). Expertise for cars and birds recruits brain areas involved in face recognition. *Nat. neurosci., 3*(2), 191-197.

Hartmann, W. M. (Ed.). (2004). *Signals, sound and sensation* (5th ed.). NY: American Institute of Physics.

Hausmann, M., Durmusoglu, G., Yazgan, Y., & Gunturkun, O. (2004). Evidence for reduced hemispheric asymmetries in non-verbal functions in bilinguals. *Journal of Neurolinguistics, 17,* 285-299.

Hsiao, J. H.-w., & Cottrell, G. W. (2009). Not all visual expertise is holistic, but it may be leftist: The case of Chinese character recognition. *Psychological Science, 20*(4), 455-463.

Hsiao, J. H.-w., Shieh, D. X., & Cottrell, G. W. (2008). Convergence of the visual field split: Hemispheric modeling of face and object recognition. *Journal of Cognitive Neuroscience, 20*(12), 2298-2307.

Ivry, R. B., & Robertson, L. C. (1998). *The Two Sides of Perception*. Cambridge: MIT Press.

Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: a module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience, 17*(11), 4302-4311.

Lades, M., Vorbruggen, J. C., Buhmann, J., Lange, J., Malsburg, C. v. d., Wurtz, R. P., & Konen, W. (1993). Distortion Invariant Object Recognition in the Dhynamic Link Architecture. *IEEE T. Comput., 42*(3), 300-311.

Maurer, U., & McCandliss, B. D. (2007). The development of visual expertise for words: The contribution of eletrophysiology. In E. L. Grigorenko & A. Naples (Eds.), *Single-word reading: Cognitive, behavioral and biological perspectives* (pp. 43-64). NJ: Erlbaum.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends Cogn. Sci., 7*(7), 293-299.

Nicholls, M. E. R., Wood, A. G., & Hayes, L. (2001). Cerebral asymmetries in the level of attention required for word recognition. *Laterality, 6*(2), 97-110.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113.

Sanger, T. D. (1989). An optimality principle for unsupervised learning. In D. Touretzky (Ed.), *Adv. Neur. In.* (Vol. 1). San Mateo: Morgan Kaufmann.

Sewell, D. F., & Panou, L. (1983). Visual field asymmetries for verbal and dot localization tasks in monolingual and bilingual subjects. *Brain and Language, 18,* 28-34.

Tan, L. H., Liu, H.-L., Perfetti, C. A., Spinks, J. A., Fox, P. T., & Gao, J.-H. (2001). The neural system underlying Chinese logograph reading. *NeuroImage, 13,* 836-846.

Tan, L. H., Spinks, J. A., Gao, J.-H., Liu, H.-L., Perfetti, C. A., Xiong, J., et al. (2000). Brain activation in the processing of Chinese characters and words: a functional MRI study. *Human Brain Mapping, 10,* 16-27.

Tzeng, O. J. L., Hung, D. L., Cotton, B., & Wang, W. S.-Y. (1979). Visual lateralisation effect in reading Chinese characters. *Nature, 282,* 499-501.