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The modulation of word type frequency on hemispheric lateralization of visual word recognition: Evidence from modeling Chinese character recognition

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Abstract

In Chinese orthography, a dominant structure exists in which a semantic radical appears on the left and a phonetic radical on the right (SP characters); the minority, opposite arrangement also exists (PS characters). Recent studies showed that SP character processing is more left hemisphere (LH) lateralized than PS character processing; nevertheless, it remains unclear whether this is due to phonetic radical position or character type frequency. Through computational modeling with artificial lexicons, in which we implement a theory of hemispheric asymmetry in perception but do not assume phonological processing being LH lateralized, we show that the difference in character type frequency alone is sufficient to exhibit the effect that the dominant type has a stronger LH lateralization than the minority type. This effect is due to higher visual similarity among characters in the dominant type than the minority type, demonstrating the modulation of word type frequency on hemispheric lateralization.

Keywords: hemispheric asymmetry, word type frequency, Chinese character recognition, computational modeling.

Introduction

Chinese phonetic compound characters are a major type of characters in Chinese orthography; they comprise about 81% of the 7,000 frequent characters in a Chinese dictionary (Li & Kang, 1993). A phonetic compound consists of a semantic radical and a phonetic radical. The semantic radical usually has information about the character meaning, whereas the phonetic radical usually has information about the character pronunciation. Most phonetic compounds have a left-right structure; a dominant arrangement exists in which a semantic radical appears on the left and a phonetic radical on the right (SP characters). This character type comprises about 90% of all left-right structured phonetic compounds. The opposite, minority (10%) arrangement also exists (PS characters; Hsiao & Shillcock, 2006; Figure 1).

Recent studies have suggested that SP and PS characters are processed differently in the brain. For example, Hsiao, Shillcock, and Lee (2007) showed that in a homophone judgment task, SP characters elicited larger N170 ERP amplitude in the left hemisphere (LH) than the right hemisphere (RH), whereas PS characters elicited similar amplitude in both hemispheres. Consistent with this finding, Hsiao and Liu (2010) showed a right visual field (RVF)/LH advantage in naming SP characters and no hemispheric lateralization in naming PS characters. This result suggests that SP character processing is more LH lateralized than PS character processing. The authors argued that this effect may be due to the dominance of SP characters in the lexicon that makes the readers opt to obtain phonological information from the right side of a character, and thus the automaticity of phonological processing in the recognition of SP characters is superior to PS characters; consequently SP character processing involves more LH phonological modulation (Maurer & McCandliss, 2007).

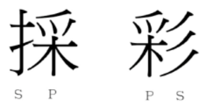

Figure 1: Examples of Chinese SP and PS characters. The two characters have the same phonetic radical and the same pronunciation [cai3] in Pinyin; their phonetic radicals also have the same pronunciation [cai3].

Here we aim to examine whether this lateralization difference between SP and PS characters can emerge purely due to the difference in their character type frequency in the lexicon, without assuming phonological processing being LH lateralized. We use a model (Hsiao, Shieh, & Cottrell, 2008) that implements a theory of hemispheric asymmetry in perception, Double Filtering by Frequency (DFF; Ivry & Robertson, 1998). The theory posits that visual information coming into the brain goes through two frequency-filtering stages: the first stage involves selection of a task-relevant frequency range, and at the second stage, the LH amplifies high spatial frequency (HSF) information, whereas the RH amplifies low spatial frequency (LSF) information. We introduce our model below.

In human visual pathways, the visual field is divided vertically into two hemifields, which are initially contralaterally projected to different hemispheres. Hsiao et al. (2008) conducted a computational modeling study aiming to examine at which processing stage this split information converges. They proposed three models with different timings of convergence: early, intermediate and late (Figure 2), and examine whether the model could account for the effect that a chimeric face made from two left half-faces (from the viewer's perspective) are usually judged more similar to the original face than the one made from two right half-faces (e.g., Gilbert & Bakan, 1973). They showed that both the intermediate and late convergence models were able to account for the effect, whereas the early convergence model was not.

Hsiao et al.'s (2008) model adopted several known observations about visual anatomy and neural computation: Gabor filter responses over the input images were used to simulate neural responses of cells in the early visual system (Lades et al., 1993); Principal Component Analysis (PCA), a biologically plausible linear compression technique (Sanger, 1989), was used to simulate possible information extraction processes beyond the early visual area; this PCA representation was then used as the input to a two-layer neural network (Figure 3). They also implemented the DFF theory in the model by using two sigmoid weighting functions to assign different weights to the Gabor filter responses in the two hemispheres (Figure 3).

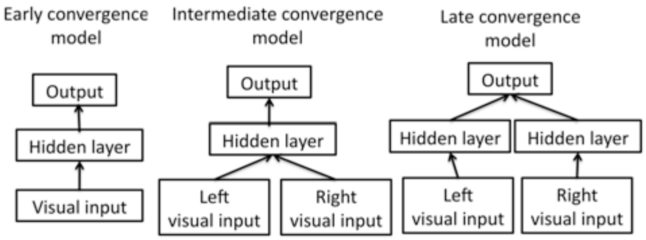

Figure 2: Hemispheric models with different timing of convergence (Hsiao et al., 2008).

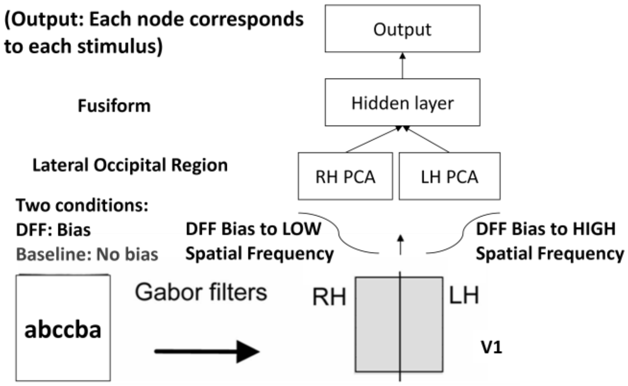

Figure 3: Hsiao et al.'s model (2008).

Here we apply Hsiao et al.'s intermediate convergence model (2008) to visual word recognition and examine whether the hemispheric lateralization difference between SP and PS character processing can emerge purely due to their difference in character type frequency in the lexicon. Cheung and Hsiao (2010) recently used the same model and demonstrated that visual and task characteristics of a writing system alone could account for hemispheric asymmetry difference in visual word recognition between different languages, without assuming phonological processing being LH lateralized. Specifically, they showed that (a) the more similar the words are in the lexicon, the more HSFs are required, leading to a stronger LH lateralization; and (b) alphabetic mapping from orthography to phonology requires more HSFs than logographic mapping, resulting in a stronger LH lateralization. In alphabetic mapping, visual word recognition involves a systematic mapping from word components to corresponding components in the pronunciation (i.e. grapheme-phoneme correspondence). In this condition, word recognition requires decomposition of word input into components in order to map them to corresponding phonemes, and thus requires more HSFs. In contrast, in logographic mapping, each word input is mapped to a pronunciation at the syllable level and there is no systematic mapping between word components and pronunciation components. Consequently, word recognition in this condition does not require decomposition of word input into components, and thus is more RH lateralized. This result is consistent with the literature: the processing of visual word recognition in alphabetic languages is usually more LH lateralized (e.g., English: McCandliss, Cohen, & Dehaene, 2003; Spanish: Hernandez, Nieto, & Barroso, 1992; Hebrew: Bentin, 1981; Japanese phonetic script kana: Hanavan & Coney, 2005; Korean Hangul words: Endo, Shimiza, & Nakamura, 1981) compared with the processing of Chinese characters, a logographic language (e.g., Tzeng et al., 1979; Leong et al., 1985).

Thus, because of the dominance of the SP structure in the Chinese lexicon, it is possible that (a) SP characters may look visually more similar to each other compared with PS characters, leading to a stronger LH lateralization. Alternatively, it may also be that (b) Chinese readers opt to decompose an SP character into radicals, map the right radical to the corresponding pronunciation, and use this information to facilitate the retrieval of the character pronunciation; in contrast, they may not attempt to decompose a PS character since they are not used to obtaining phonological information from the left radical. This decomposition effect may lead to a stronger LH lateralization in SP character processing than PS characters.

Here we test these two hypotheses through computational modeling, since models give us good control over variables that are difficult to tease apart in human studies. In the Chinese orthography, in addition to character type frequency, SP and PS characters differ in at least three other aspects: (1) Position of the phonetic radical; (2) Character configuration in terms of visual complexity: since semantic radicals usually have fewer strokes than phonetic radicals, SP characters tend to have a right-heavy configuration, whereas PS characters usually have a left-heavy configuration. (3) Character information structure (in terms of entropy): Since there are more phonetic radical types than semantic radical types (the ratio is about 8 to 1; Hsiao & Shillcock, 2006), in SP characters there is more information on the right, whereas in PS characters there is more information on the left[1]. To examine the influence of character type frequency on hemispheric lateralization, in Experiment 1 we created artificial lexicons with SP and PS structures and manipulated their character type frequency (equal frequency vs. SP dominant vs. PS dominant) with all the other three factors controlled. To examine how position of the phonetic radical influence lateralization, in Experiment 2, in addition to character type frequency, we also manipulated position of the phonetic radical, with both radical visual complexity (factor (2)) and character information structure (factor (3)) controlled.

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[1] Another difference between SP and PS characters is that the percentage of regular characters is higher in SP characters than in PS characters (a regular character has the same pronunciation as its phonetic radical). Here we focus on structural differences and do not aim to examine the factor of pronunciation regularity; in the artificial lexicons we assume all characters are regular.

Modeling Methods and Results

In our model we first applied a 10 x 10 rigid grid of 2D Gabor filters (Daugman, 1985) to the character images; at each grid point we applied Gabor filters with 8 orientations and 5 frequency scales (following Hsiao et al., 2008; Cheung & Hsiao, 2010). Gabor filter responses in different scales were subsequently given different weights; two conditions were created: (1) the unbiased condition, in which Gabor responses in all scales were given equal weights in both visual hemifields, and (2) the biased condition, in which larger weights were given to HSF responses in the RVF/LH, and larger weights were given to LSF responses in the left visual field (LVF)/RH (the second stage of the DFF; the weights were determined by a sigmoid function (Figure 3)). The difference in the model's behavior between the two conditions thus reflected the influence of frequency bias (DFF) on the lateralization effects.

The LVF and RVF Gabor representations were then compressed by PCA separately into two 50-element representations (100 elements in total; Hsiao et al., 2008), which were then z-scored to equalize the contribution of each element. The z-scored PCA representation was then used as the input to a two-layer neural network (NN). The NN was trained to recognize input images by mapping them to corresponding pronunciations at the syllable level (the pronunciation of each Chinese character only has one syllable); there were 15 nodes in the output layer, corresponding to pronunciations of 15 phonetic radicals; each character had the same pronunciation as its phonetic radical[1]. The training continued until the performance on the training set reached mean-square-error 0.001 or until it could not be further improved. Gradient descent with an adaptive learning rate was used as the training algorithm. To measure lateralization effects, we damaged either the LH PCA or the RH PCA representation of the test images by setting the representation to zeros; a LH lateralization index was defined as the accuracy difference between recognizing a RH/LVF damaged character (only LH/RVF representation was available) as the original image and recognizing a LH/RVF damaged character (only RH/LVF representation was available) as the original image. A higher index hence corresponded to a stronger LH lateralization and indicated the model's reliance on HSF information.

In the following experiments, for each condition we ran the model with 20 different lexicons, each containing 100 pseudo-characters; for each character there were 8 images in different fonts, with 4 of them used for training and the other 4 for testing (counterbalanced across simulation runs). The image size was 60 x 60 pixels. For each lexicon, 10 different sets of NN weight initialization were used, and the average accuracy over the 10 runs was used for data analysis. This was to minimize the fluctuation in accuracy caused by the random weight initialization. These 10 sets of weight initialization were the same across different conditions to closely match the models.

Although our model assumed split architecture (i.e. the split model; see Ellis & Brysbaert, 2010), some have argued that the fovea representation for reading is bilaterally projected (e.g. Jordan & Paterson, 2009). Thus, in separate simulations we projected the same word input to both hemispheres (i.e. the bilateral model) and compared it with the split architecture.

Experiment 1

Here we examined the influence of character type frequency on hemispheric lateralization of character processing, with all the other three factors controlled: (1) position of the phonetic radical, (2) character configuration, and (3) character information structure. We created artificial lexicons with pseudo-characters and manipulated the proportions of SP and PS characters. Each pseudo-character was generated by concatenating two mirror-symmetric radicals. To control for factor (1), characters formed a top-bottom configuration (Figure 4) so that the phonetic radical was not biased to either the LVF or RVF. One of the two radicals was randomly chosen from a "P list" (phonetic radicals), while the other was randomly chosen from "S_1 list" (semantic radicals) if it was placed on the top (SP characters, for the current purpose), or from "S_2 list" if it was placed on the bottom (PS characters). Each list contained 15 radicals, so there were 15x15 (225) possible combinations in total for either SP or PS characters. This was to simulate the Chinese orthography in which SP and PS characters may have the same phonetic radicals, but the semantic radicals are usually different.

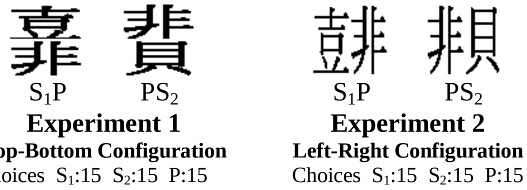

Figure 4: Stimuli images for the 2 experiments.

Each artificial lexicon contained 100 pseudo-characters. The SP characters were randomly selected from different combinations of S_1-list radicals and P-list radicals; the semantic radicals (S_2-list) of the PS characters had the same combinations with P-list radicals as those in the SP characters. When a majority type of characters existed, the combinations used for the minority type was randomly selected from those for the majority type. The radical choices in S_1 and S_2 lists were counterbalanced across simulation runs. The radicals used were all existing stroke patterns in Chinese, and the numbers of strokes of the radicals in the 3 lists were matched (about 6.4 strokes on average; factor (2)). The same number of radicals was used for the P list and S lists, so that the amount of information for recognition defined by entropy on either side of the characters was balanced (i.e. factor (3)). Mirror images were used in half of the simulation runs to counterbalance possible low-level featural differences between the two sides of the characters.

There were 3 variables in the design: Spatial frequency (SF) bias (unbiased vs. biased), character type (SP vs. PS), and type frequency (SP Dominant (90% SP, 10% PS) vs. PS

Dominant (10% SP, 90% PS) vs. equal frequency (50% SP, 50% PS))[2]. The dependent variable was LH lateralization index. The results showed a significant SF bias effect (F(1, 35) = 3509.536, $p < 0.001$; Figure 5, top row): In the biased condition, the model exhibited less LH lateralization (LSF preference), consistent with the literature showing a RH (LSF) lateralization in Chinese character recognition (e.g., Hsiao & Cottrell, 2009). In addition, there was an interaction between SF bias, character type, and type frequency (F(2, 70) = 101.427, $p < 0.001$; Figure 5, top row): in the unbiased condition, there was no effect of character type or type frequency. In contrast, in the biased condition, there was an interaction between character type and type frequency (F(2, 72) = 222.974, $p < 0.001$): when SP and PS characters had an equal type frequency, there was no LH lateralization difference; when SP type was dominant, SP character processing was more LH lateralized (t(39) = 13.646, $p < 0.001$), whereas when PS type was dominant, PS character processing was more LH lateralized (t(39) = 12.534, $p < 0.001$). Thus, consistent with our prediction, the dominant type had a stronger LH (HSF) lateralization. Similar effects were also obtained in the bilateral models.

To test whether the above effects were due to the existence of a phonetic radical that biased phonological information to one component (i.e. whether decomposition was required), in a separate simulation, instead of mapping each character systematically to the pronunciation of its phonetic radical, we mapped each character to a randomly assigned pronunciation in the output layer (i.e. logographic mapping). The results (figure 5, bottom row) showed a similar interaction between SF bias, character type and type frequency (F(2, 72) = 79.881, $p < 0.001$): no effect of character type or type frequency was observed in the unbiased condition; in contrast, in the biased condition there was an interaction between character type and type frequency (F(2, 72) = 165.902, $p < 0.001$): the dominant character type had a stronger LH lateralization than the minority type. This result suggested that the type frequency effect does not require the existence of a phonetic radical; it emerged when the phonological information was not biased to one radical and thus no decomposition was required. When we compared the two mapping methods (regular vs. logographic mappings) in the biased condition, there was a significant mapping method effect (F(1, 72) = 101.161, $p < 0.001$): the regular mapping condition had a stronger LH lateralization, suggesting that when the phonological information was biased to one radical, and thus decomposition of a character into radicals might be required, the model had a stronger LH (HSF) lateralization.

A further analysis showed that the stronger LH lateralization in the dominant character type was related to a higher visual similarity among characters in the dominant type compared with the minority type. The single linkage (shortest distance) method was used to calculate the shortest distance between the Gabor responses of a character and all the other characters, as a measure of how similar this character was to the other characters (e.g., Mardia, Kent, & Bibby, 1980); the average of this shortest distance was used as the similarity measure for each character type in the lexicon. The results showed that characters in the dominant type had a higher similarity among each other compared with those in the minority type (SP dominant: t(60.348) = 7.829, $p < 0.01$; PS dominant: t(60.391) = -9.686, $p < 0.001$). In addition, in both the regular and logographic mapping conditions, the LH lateralization was significantly correlated with the similarity measure: the more similar the characters were in a character type, the stronger the LH lateralization was in processing the character type (Regular Mapping: r = -0.117, p = 0.01; Logographic Mapping: r = -0.131, $p < 0.01$). This effect suggests that the level of LH lateralization in different character types may be mainly due to visual similarity among characters.

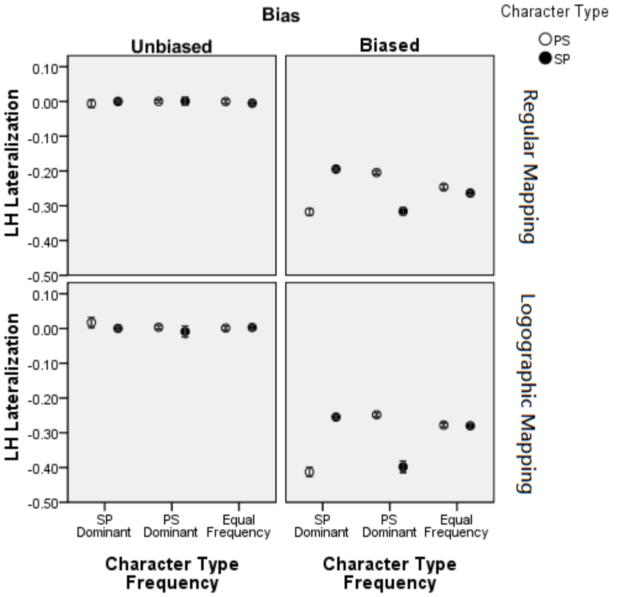

Figure 5: LH lateralization index in Experiment 1.

Experiment 2

Here we used the same settings and radicals as Experiment 1, except that the radicals were arranged horizontally to form left-right structures (Figure 4). We examined the factors of type frequency and position of the phonetic radical (i.e. factor (1); no mirror images were used here since the position of the phonetic radical was manipulated).

In contrast to Experiment 1, the results showed that in both unbiased and nonbiased cases, there was an interaction between character type and type frequency (unbiased: F(2, 76) = 151.836, $p < 0.001$; biased: F(2, 76) = 167.338, $p < 0.001$; Figure 6): in general, SP character processing was lateralized to the RVF/LH, where the phonetic radical appeared, whereas PS character processing was lateralized to the LVF/RH, regardless of SF bias. This effect was also modulated by type frequency: this lateralization effect due to position of the phonetic radical was weaker in the

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[2] We also included 2 Latin-square variables to account for the counterbalance of S_1 and S_2 lists, and using original or mirror images (see, e.g., Brysbaert, 2007). Greehouse-Geisser correction was applied whenever the assumption of sphericity was not met.

minority character type than the dominant type. In addition, this interaction was stronger in the unbiased than the biased condition (SF bias x character type x type frequency, F(2, 76) = 9.765, $p < 0.001$), suggesting additional influence from the SF bias .

In contrast to the split model, in the bilateral model, the character type by type frequency interaction was only observed in the biased (F(2, 76) = 362.069, $p < 0.001$) but not in the unbiased condition (n.s.); there was a significant three-way interaction between SF bias, character type, and type frequency (F(2, 76) = 312.876, $p < 0.001$). In the biased condition, the dominant character type had a stronger LH lateralization (SP dominant: t(39) = 14.354, $p < 0.001$; PS dominant: t(39) = -17.558, $p < 0.001$; equal frequency: t(39) = -1.111, n.s.); in contrast, in the unbiased condition, no effect of character type or type frequency was observed. This effect was similar to that in Experiment 1, in which the two sides of the model also received the same amount of information about the character pronunciation. Here the split and bilateral models provided different testable predictions that can be further examined by human experiments.

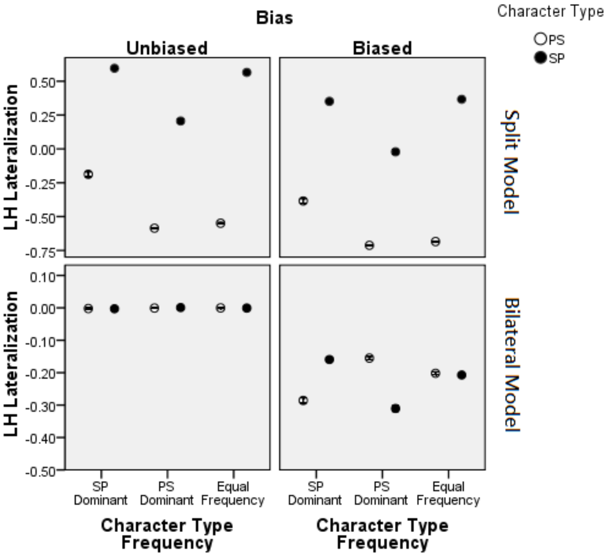

Figure 6: LH lateralization index in Experiment 2.

Conclusion and Discussion

Here we investigated the modulation of word type frequency on hemispheric lateralization of visual word recognition through modeling Chinese phonetic compound recognition. We contrasted the processing of SP and PS characters, in which the phonetic radical appeared in opposite positions. Previous studies have shown that SP character processing involves a stronger LH lateralization than PS character processing; nevertheless, it remains unclear whether this effect is because the processing of the dominant SP structure has stronger automaticity of LH phonological processing than that of the minority PS structure, or simply due to differences in the spatial frequency content that is important for recognizing a dominant or minority character type in the lexicon.

Through computational modeling, in which we implemented a theory of hemispheric asymmetry in perception (the DFF theory) but did not assume a LH lateralized phonological processing center, we showed first in Experiment 1 that when all the other possible factors that may influence lateralization were controlled, including (1) position of the phonetic radical, (2) visual complexity of the radicals, and (3) character information structure defined by entropy, hemispheric lateralization differences could emerge purely due to a difference in character type frequency: the dominant character type had a stronger LH (HSF) lateralization than the minority type (in the biased condition, Figure 5); this effect was obtained regardless of whether the model assumed a split architecture or a non-split, bilateral projection. In addition, this effect did not require the existence of a phonetic radical that biased phonological information to one component, as this effect also emerged in the logographic mapping condition, in which there was no systematic relationship between phonetic radicals and character pronunciations. Further analysis suggests that this effect was mainly due to higher visual similarity among characters in the dominant type than those in the minority type. With a fixed number of radicals, when we gradually increased the number of characters in a character type, it became more likely that some characters shared common radicals and thus were visually similar to each other. This effect was consistent with the previous finding that visual similarity among words in a lexicon can influence hemispheric lateralization in visual word recognition (Cheung & Hsiao, 2010).

Using a similar model, Cheung and Hsiao (2010) have previously shown that when a visual word recognition task requires decomposition of a word into components in order to map them to phonemes/pronunciation components (e.g. alphabetic reading), more HSF information is required compared with when this decomposition is not required (e.g., logographic reading). Consistent with this finding, the current data also showed that in the regular mapping condition, in which the phonetic radical consistently provided information about the character pronunciation, the model had a stronger LH lateralization than the logographic mapping condition (in the biased condition, Figure 5); this effect may be due to the existence of a phonetic radical encouraged decomposition of a character into radicals in order to identify the phonetic radical, leading to a higher demand on HSF information.

In Experiment 2, we examined the effect of position of the phonetic radical. The data showed that in the split model, position of the phonetic radical modulated the lateralization effect, regardless of whether the DFF theory was applied. This effect was due to phonological information being on one side of a character, and thus the processing was lateralized to one visual hemifield; in addition, this phonetic radical position effect was weaker in the minority character type than in the dominant type. In contrast, this effect was not observed in the bilateral model, since the character input was bilaterally projected and thus the phonetic radical was available in both hemispheres. The results of the bilateral model were consistent with Experiment 1: The dominant character type had a stronger LH lateralization when the DFF theory was applied. Here our data predicted different behavior between the split and bilateral models; this difference may be useful for resolving the controversy over whether foveal representation is split and contralaterally projected, or bilaterally projected (e.g. Ellis & Brysbaert, 2010; Jordan & Paterson, 2009).

Thus, our modeling data suggest that the stronger LH lateralization in SP character processing than PS character processing in Chinese character recognition can emerge without assuming phonological processing being LH lateralized (cf. Hsiao & Liu, 2010). More specifically, this effect may be due to a higher visual similarity among SP characters than PS characters, because of a much greater number of SP characters than PS characters in the lexicon (Experiment 1). In addition, under the split fovea assumption, this effect may also be influenced by position of the phonetic radical in a character (Experiment 2).

In summary, through modeling Chinese phonetic compound recognition, here we show that hemispheric lateralization of visual word recognition can be modulated purely by word type frequency. This effect is due to a higher visual similarity among words in the dominant type than the minority type. Further investigation will examine other factors that may influence lateralization effects in visual word recognition, and whether this word type frequency effect can also be found in other languages.

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