Hemispheric Differences Emerge from Perceptual Learning: Evidence from Modeling Chinese Character Pronunciation

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Abstract

In Chinese orthography, a dominant character structure exists in which a semantic radical appears on the left and a phonetic radical on the right (SP characters); a minority opposite arrangement also exists (PS characters). As the number of phonetic radical types is much greater than semantic radical types, in SP characters the information is skewed to the right, whereas in PS characters it is skewed to the left. Through training a symmetrical split fovea model for SP and PS character recognition, we show that hemispheric differences emerged as a consequence of the fundamental structural differences in information between SP and PS characters. The modeling data also matches well with behavioral naming performance. This work suggests that perceptual learning is one of the factors that accounts for hemispheric differences in visual word recognition.

Keywords: Connectionist modeling; Chinese character recognition; hemispheric differences; perceptual learning.

Introduction

Hemispheric differences in visual word recognition have been consistently reported. For instance, there is a classical right visual field (RVF) advantage in reading English words, demonstrated first in tachistoscopic recognition (e.g., Bryden & Rainey, 1963) and subsequently in other word recognition tasks, including lexical decision (Faust, Babkoff, & Kravetz, 1995), and word naming (Brysbaert & d'Ydewalle, 1990). This RVF advantage has been argued to be linked to the superiority of the left hemisphere (LH) in language processing and shown to interact with sex and handedness (e.g., Voyer, 1996; Kim, 1994).

In addition to this hemispheric dominance account of the RVF advantage, alternative explanations have also been proposed. Mondor and Bryden (1992) proposed an attentional advantage model, which suggests that in addition to a direct access to the LH, this RVF advantage can also be influenced by the distribution of attention; the LH is able to process verbal stimuli with fewer attentional resources allocated, compared with the RH, and hence gives rise to this RVF advantage. Evidence supporting this model comes from several cueing experiments, showing that verbal stimuli presented to the left visual field (LVF)/right hemisphere (RH) had stronger cueing effects than those presented to the RVF/LH, because they required more attentional resources (e.g., Nicholls, Wood, & Hayes, 2001).

In Chinese character recognition, in contrast to English, a LVF/RH advantage has been reported in tachistoscopic recognition; this phenomenon has been argued to reflect the RH superiority in handling holistic pattern recognition tasks or a more efficient lexical interpretation of character stimuli in the RH (e.g., Tzeng, Hung, Cotton, & Wang, 1979). As for phonological processing in Chinese character recognition, Weekes and Zhang (1999) reported phonological priming effects on phonetic compound recognition when the characters were presented in the RVF but not LVF. Yang and Cheng (1999) also showed that, in a character recognition task, when the orthographic similarity of two alternative items for choice was manipulated, there was an LVF advantage effect; in contrast, when the phonological similarity of two alternative items for choice was manipulated, there was a prominent RVF advantage effect. In short, previous divided visual field studies in Chinese character recognition usually exhibited a LVF advantage for orthographic processing and a RVF advantage for phonological processing.

In the current study, we examine the possibility that hemispheric differences in visual word recognition can emerge purely from perceptual learning, or more specifically, the information structure of the word stimuli to which the readers have long been exposed. We first report the predictions from a computational model of word recognition, and then examine these predictions through a corresponding behavioural experiment. The materials we used were a major type of Chinese characters, *phonetic compounds*, in order to utilize their distinct information structure in this examination. We introduce the structures of these Chinese characters below.

A Chinese phonetic compound consists of a semantic radical, that signifies the meaning of the character, and a phonetic radical, that typically contains partial information about the pronunciation of the character. For current purposes, we refer to a character whose pronunciation is the same as its phonetic radical as a regular character; characters whose pronunciations are the same as their phonetic radical but with a different tone are called semiregular characters; and those whose pronunciations are different from their phonetic radicals are termed irregular characters. In Chinese phonetic compound recognition, a regularity effect has been reported: regular characters are named faster than irregular characters (e.g., Hue, 1992). Most of the phonetic compounds have a left-right structure; about 90% of them have their semantic radical on the left and the phonetic radical on the right. These characters are referred to as SP characters. The other 10% have the opposite arrangement, with the phonetic radical on the left and the semantic radical on the right, termed PS characters (Hsiao & Shillcock, 2004; see Figure 1). Also, in Chinese orthography, the phonetic radical types are much more numerous than the semantic radical types; the ratio is about ten to one (Harbaugh, 1998). In other words, there is greater variability in the phonetic radical. Hence, in SP characters, the information is skewed to the right, whereas in PS characters, the information is skewed to the left. Given the dominant percentage of SP characters compared with PS characters, the overall information distribution is skewed to the right. As we show later, the distinction between the structures of SP and PS characters and the overall information skew allow us to demonstrate how hemispheric differences in visual character recognition can emerge from perceptual learning.

訟 頌

SP character PS Character

Figure 1. An SP and a PS character.

We first conducted a computational examination with a split fovea model of Chinese character recognition (Hsiao & Shillcock, 2004; 2005a). The split fovea model assumes a precise vertical split at fixation, with the two halves of a centrally fixated word initially contralaterally projected to two different hidden layers, by analogy with the two hemispheres. This foveal splitting phenomenon has been demonstrated in several anatomical and behavioral studies (e.g., Lavidor & Walsh, 2004), and has also been shown to have fundamental implications for hemispheric processing of visual word/character recognition (Shillcock, Ellison, & Monaghan, 2000). The split fovea model hence enables us to examine hemispheric processing in reading. We have reported previously the model's behavior for centrally presented characters (Hsiao & Shillcock, 2005a); the modeling successfully addressed sex differences observed in naming SP and PS characters (Hsiao & Shillcock, 2005b). In the current simulation, we focus on the model's behavior when characters are presented entirely to the left or right of fixation, that is, in the LVF or RVF (Figure 2; See Simulations for details)[1]. We show that in a model with a completely symmetrical architecture, hemispheric differences emerge as a consequence of the information structure of the materials with which the network is trained. We then show that human behavior is well predicted by such modeling, suggesting the influence of perceptual learning on the observed hemispheric differences.

[1] For the model's behavior when characters are centrally presented and its connection with human data, please refer to Hsiao and Shillcock (2005a; 2005b).

Simulations

Figure 2 shows the split fovea model of Chinese character recognition (Hsiao & Shillcock, 2005a), which maps an orthographic representation, defined by basic stroke patterns in Chinese orthography, to a corresponding feature-based phonological representation. The input layer is split with respect to a fixation point; the two halves of the input layer are projected to left hidden layer (LHL) and right hidden layer (RHL) respectively to simulate the initial contralateral projections to different hemispheres. The interconnections between the hidden layers are by analogy with the corpus callosum (for the importance of these interconnections, see Hsiao & Shillcock, 2004).

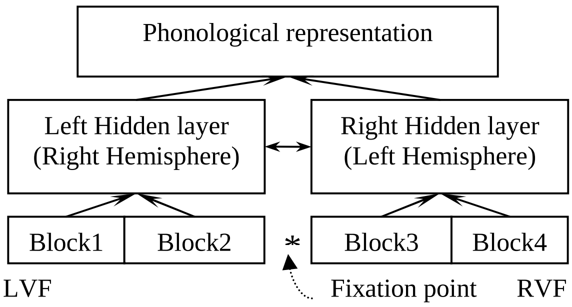

Figure 2. The split-fovea model of Chinese character recognition.

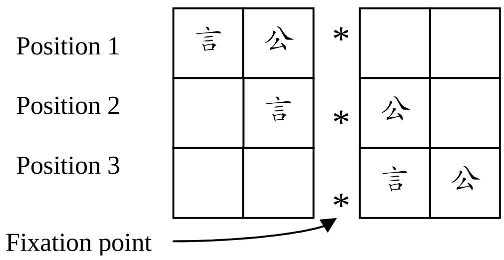

Figure 3: Three fixation positions in the input layer.

During the simulation, eye fixation behavior was idealized into three different fixation positions, as shown in Figure 3 (Hsiao & Shillcock, 2004). In order to accommodate such representations, the input layer contained four blocks. When a character was presented in position 1, the current fixation was to the right of the character; in position 2, the current fixation was between the two radicals; in position 3, the fixation was to the left of the character. During training, each character was presented according to its log token frequency, and equally distributed among the fixation positions. This equal presentation frequency among the fixation positions reflected the finding that there is no tendency for the eyes to land more frequently at a particular position in a character during

Chinese text reading (e.g., Tsai & McConkie, 2003)[2]. We trained the network with 2,159 of the most frequent left-right structured phonetic compounds (i.e., SP and PS characters), together with their phonetic radicals that can also be stand-alone characters (presented in block 2 and 3 only), and examined its behavior in different fixation positions (for more details of the simulation, see Hsiao & Shillcock, 2004; 2005a).

Results

We ran the model ten times and analyzed its average performance with ANOVA. The independent variables were fixation position (position 1, 2, and 3), character regularity (regular/semiregular vs. irregular), character frequency (high vs. low), and position of the phonetic radical (SP vs. PS). The dependent variable was averaged summed squared error.

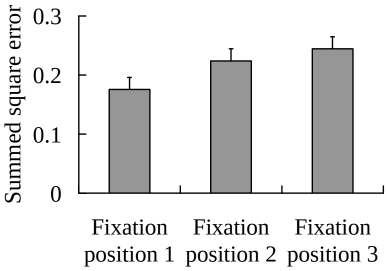

Figure 4: Model's performance in three different fixation positions.

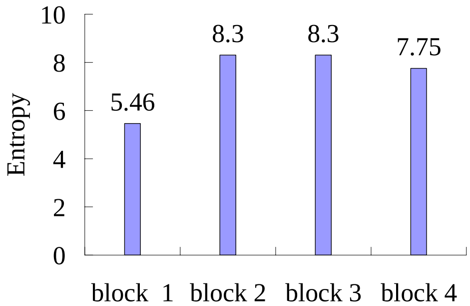

Figure 5: Entropy Analysis of the four blocks in the input layer during training (Hsiao & Shillcock, 2005a).

The results showed a main effect of fixation position ($F(2, 4032) = 16.845$, $p < 0.001$), with the best performance in fixation position 1 and the worst in fixation position 3 (Figure 4). This phenomenon can be explained by the overall rightward information skew in the lexicon. Compared with the LHL, the RHL had a heavier processing demand due to the greater variability, or entropy in information theory, on the right of the characters (Figure 5). Consequently, the model had the best performance when characters were presented in fixation position 1, *i.e.*, when the processing of the character mainly depended on the LHL; and had the worst performance when characters were presented in fixation position 3, *i.e.*, when the processing of the character mainly depended on the RHL.

Also, there was a significant three-way interaction between fixation position, character regularity, and position of the phonetic radical ($F(2, 4032) = 8.183$, $p < 0.001$ with the Greenhouse-Geisser correction). When we examined the model's performance in different fixation positions separately, the interaction between character regularity and position of the phonetic radical was the strongest in fixation position 1 ($F(1, 2151) = 11.336$, $p = 0.001$) and the weakest in fixation position 3 ($F(1, 2151) = 3.889$, $p = 0.049$; see Figure 6). This phenomenon can be explained by a denser mapping problem presented to the model when characters were presented in fixation position 3 than in fixation position 1 (Figure 5). When PS characters were presented in fixation position 1, the model faced a sparser mapping problem since the phonologically important part of the characters (i.e., the phonetic radical) was presented in block 1, which had the lowest level of entropy; consequently, the model had adequate processing resources to remember individual orthography-to-phonology mappings without generalization. Hence, there was no regularity effect observed when PS characters were presented in fixation position 1 ($F(1, 213) < 1$; Figure 6)[3]. When PS characters were presented in fixation position 3, the denser mapping problem, compared with fixation position 1, demanded more generalization in the network. Hence, the regularity effect became significant when PS characters were presented in fixation position 3 (Figure 6).

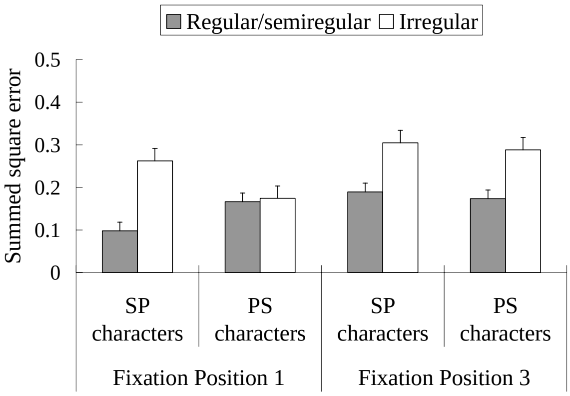

Figure 6: Interaction between character regularity and position of the phonetic radical in fixation position 1 and 3. The error bars show standard errors.

In contrast, the phonetic radical of a SP character always fell in a block with a high entropy level (Figure 5), and hence there was a strong regularity effect across the three fixation positions. Consequently, the interaction between

[2] This phenomenon may be because the length of a character is too short for the effects to emerge (see Tsai & McConkie, 2003).

[3] Note that PS characters also have a smaller percentage of regular characters than SP characters; it may partly explain the weaker regularity effect for PS characters.

regularity and position of the phonetic radical was strongest when characters were presented in fixation position 1 and the weakest in fixation position 3. Note that in fixation position 3, where the model had the densest mapping problem, the model had to generalize both the majority SP and the minority PS characters to a similar extent and consequently SP and PS characters had an equally strong regularity effect (Figure 6).

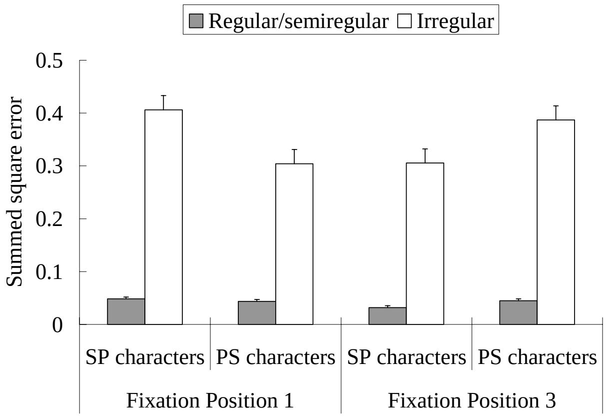

Figure 7: Interaction between character regularity and position of the phonetic radical in fixation position 1 and 3 when the model was trained with the artificial lexicon. The error bars show standard errors.

In a separate simulation, we created an artificial lexicon with the same number of SP and PS characters, in order to examine the baseline behavior of the model when there is no overall information skew in the lexicon; the results reflect the fundamental structural differences between the processing of SP and PS characters. The artificial lexicon consisted of 40 phonetic, 10 left semantic, and 10 right semantic radicals; both SP and PS characters have the same percentage of regular and irregular characters as the real lexicon (for details see Hsiao & Shillcock, 2005a). The results again showed a significant three-way interaction between fixation position, character regularity, and position of the phonetic radical ($F(2, 792) = 25.360$, $p < 0.001$ with the Greenhouse-Geisser correction). Figure 7 shows the interaction between character regularity and position of the phonetic radical in fixation position 1 and 3. In fixation position 1, SP characters had a stronger regularity effect than PS characters; this phenomenon can be explained by a higher processing demand for SP characters than PS characters, since the phonetic radicals of SP characters were presented in a block with a higher entropy value (i.e., block 2) compared with those of PS characters (block 1; Figure 8). This higher processing demand pushed the model to a higher level of generalization versus memorization, leading to a stronger regularity effect. In contrast, PS characters had a stronger regularity effect in fixation position 3 than SP characters, since their phonetic radicals were presented in a block with a higher entropy value. This phenomenon supported the claim that the level of regularity effect in different fixation positions was influenced by the processing demand presented to the model from the given fixation position. It also showed that the three-way interaction we observed when the model was trained with the real lexicon was at least partly due to the fundamental structural differences between the processing of SP and PS characters[4].

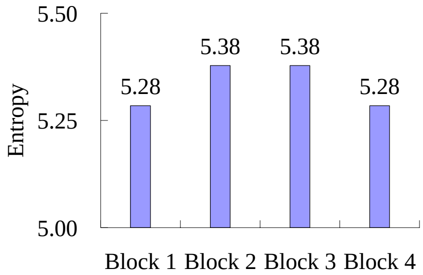

Figure 8: Entropy Analysis of the four slots in the input layer for the models trained with the artificial lexicon.

Behavioral Experiment

In order to examine the model's cognitive plausibility, we conducted a divided visual field study of Chinese character naming. Our prediction was a three-way interaction between visual field (LVF vs. RVF), character regularity, and position of the phonetic radical, as predicted by the model.

Materials & Participants

The materials consisted of the same 75 pairs of SP and PS characters used in Hsiao and Shillcock's (2005b) study. Hence, each pair shared the same phonetic radical and was matched in terms of pronunciation and token frequency; the two groups of characters (i.e., SP and PS characters) were matched as closely as possible according to syntactic class, semantic concreteness, and visual complexity of semantic radical as defined by number of strokes. Of the 75 pairs of SP and PS characters, 31 were regular or semiregular and 44 were irregular. Character frequencies were within a mid- to-high range. A further 40 SP and 20 PS filler characters, half regular and half irregular, were also used in the experiment.

We recruited 16 female and 16 male native Chinese speakers from Taiwan, with similar (university or higher) educational background and normal or corrected vision. All were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971) and with ages matched between the male and female groups.

Design & Procedure

The design of this study had three within-subject variables: position of the phonetic radical (PS vs. SP), character

[4] In separate simulations, we observed the same three-way interaction in a non-split model, in which the mapping was mediated through only a single hidden layer (see Hsiao & Shillcock, 2005a), for both the real and the artificial lexicons. It suggested that this three-way interaction was mainly due to the information structure of the stimuli, rather than the network architecture.

regularity (regular/semiregular vs. irregular), and visual field (LVF vs. RVF). The dependent variable was the time taken to begin a correct pronunciation. Characters were presented in a standard calligraphic font, each measuring approximately 1 x 1 cm^2. Participants sat in front of a screen, at a viewing distance of 115 cm. Hence, each character subtended less than one degree of visual angle and fell within foveal vision. This design was to attenuate any visual acuity difference when a character was presented in LVF or RVF (Lindell & Nicholls, 2003).

Each naming trial began with two short vertical lines presented on the screen for 500 ms. Participants were told to look at the midpoint between the two lines. The two lines were followed by a 150 ms presentation of the target character, which did not allow time for refixation. The target character was presented immediately either to the right or to the left of the initial fixation. Occasionally a 9 pt. digit was presented, instead of a character, exactly between the two lines where participants should be fixating, to ensure that participants were fixating the right place; the digit was only presented for 90 ms. Data from any participant who did not report the digits to an acceptable accuracy were rejected (cf. Brysbaert, 1994). After each presentation of a target character or a digit, participants were asked to name the character or digit as fast and as accurately as possible. We measured the response time as the time difference between the onset of the character presentation and the onset of the participant's pronunciation. The stimulus was replaced by a mask after the presentation; the mask disappeared after the onset of the participant's pronunciation. The screen then turned blank until the experimenter pressed a button to start the next trial. Participants were put into four groups, with males and females evenly distributed. The materials presented to the four groups were counterbalanced along two dimensions: presentation order of each pair of PS and SP characters (i.e., the PS character or the SP character first) and presented visual field for each character. During the experiment, the SP and PS characters in the same pair did not appear in the same block or in the same visual hemifield to minimize priming effects. Characters in each block were presented in a random order.

Results

The results showed that there was indeed a significant three-way interaction between visual field, character regularity, and position of the phonetic radical ($F(1, 30) = 4.484$, $P < 0.05$; see Figure 9): there was a significant interaction between character regularity and position of the phonetic radical in the LVF ($F(1, 31) = 4.878$, $P < 0.05$), but not in the RVF ($F < 1$). The results obtained hence matched well with the model's predictions. Because of the overall rightward information skew and the fundamental structural differences between the processing of SP and PS characters, when PS characters were presented in the LVF/RH, individual mappings between orthography to phonology could be processed without generalization; when they were presented in the RVF/LH, the denser mapping problem demanded more generalization. These phenomena gave rise to a significant interaction between visual field and character regularity ($F(1, 31) = 4.173$, $P = 0.05$) for PS characters: the regularity effect was significant only when they were presented in the RVF. In contrast, such interaction was absent for SP characters ($F < 1$); they required generalization in both LVF and RVF presentations.

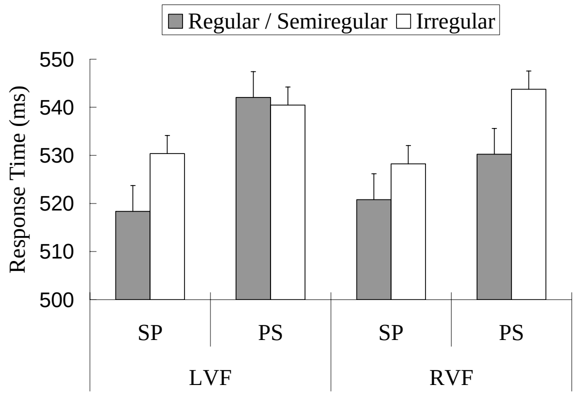

Figure 9: Three-way interaction among visual field, position of the phonetic radical, and character regularity. The error bars show standard errors.

Nevertheless, there was no main effect of visual field ($F < 1$). The model predicted a LVF advantage due to the overall rightward information skew. It is possible that such an LVF advantage was offset by the fact that the RVF has direct access to the LH, which is superior in phonological processing. Thus, Chinese character naming may involve an interplay between LVF advantage for orthographic processing and a RVF advantage for phonological processing[5].

Discussion & Conclusion

We have shown, through both computational modeling and a behavioral experiment, that hemispheric differences in processing Chinese characters might emerge from perceptual learning, or more specifically, the information structures of the characters to which the readers have long been exposed. Chinese SP and PS characters provide an important opportunity to examine this phenomenon: the fundamental structural differences in information between SP and PS characters and the overall information skew. In the computational modeling, when the network architecture was completely symmetrical, we saw a three-way interaction between visual field, position of the phonetic

[5] Note also that in this study, SP characters were responded significantly faster than PS characters, regardless of the visual field. It is possible that in hemifield-presentation conditions, characters were processed through a single processing domain (i.e., LH or RH) and hence the brain excels in processing the majority SP characters at the expense of the minority PS characters (refer to male behavior in Hsiao & Shillcock, 2005b). The smaller response times for PS characters in the RVF/LH, compared with the LVF/RH, might have reflected automaticity in the LH over phonology.

radical, and character regularity. When there was a balanced distribution between SP and PS characters, as in the artificial lexicon, the fundamental structural differences between the processing of SP and PS characters caused a stronger regularity effect for SP characters in the LVF and stronger regularity effect for PS characters in the RVF. When the distribution between SP and PS characters were unbalanced, as in the real lexicon, the same three-way interaction was observed; the overall rightward information skew demanded more processing load in the RVF, and push both SP and PS character to a similar level of generalization.

The modeling predictions matched well with the human data. In the divided visual field study of character naming, we observed the same three-way interaction as the modeling data. The results hence suggested perceptual learning of the information structures of the word stimuli as one of the factors accounting for hemispheric differences in visual word recognition. This perceptual learning account may also partly explain the attentional advantage account: for English words, contrary to Chinese characters, there is more information on the left and hence the LVF/RH may have received more processing demands and consequently the RH requires more attentional resources. Thus, this perceptual learning account can more readily accommodate data from both English and Chinese studies than can the attentional advantage model.

In addition to the information structure of characters/words, there are also some other factors which may account for hemispheric differences in character/word recognition, such as the RH superiority in handling holistic pattern recognition and the LH superiority in phonological processing, and visual acuity, which drops dramatically from the centre of fixation (Nazir, O'Regan, & Jacobs, 1991); hemisphere differences may also interact with sex of the participant. Thus, further investigation is required for a full understanding of how the two hemispheres coordinate information in visual character/word recognition.

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