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Hemisphere lateralization is influenced by bilingual status and composition of words

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ABSTRACT

It has been generally accepted that the left hemisphere is more functionally specialized for language than the right hemisphere for right-handed monolinguals. But more and more studies have also demonstrated right hemisphere advantage for some language tasks with certain participants. A recent comprehensive survey has shown that hemisphere lateralization of language depends on the bilingual status of the participants, with bilateral hemispheric involvement for both languages of early bilinguals, who acquired both languages by age of 6, left hemisphere dominance for language of monolinguals, and also left hemisphere dominance for both languages of late bilinguals, who acquired the second language after age of 6. We propose a preliminary model which takes into account both composition of stimulus words and bilingual status of participants to resolve the apparent controversies regarding hemisphere lateralization of various reading experiments in the literature with focus on Chinese characters, and to predict lateralization patterns for future experiments in Chinese word reading. The bilingual status includes early bilingual, late bilingual and monolingual. However, we have tested this model only with late Chinese–English bilingual participants by using a Stroop paradigm in this paper, though the aim of our model is to disentangle the controversies in the lateralization effect of Chinese character reading. We show here with stimuli written in Chinese single characters that the Stroop effect was stronger when the stimuli were presented to the right than to the left visual field, implying that the language information and color identification/naming may interact more strongly in the left hemisphere. Therefore, our experimental results indicate left hemisphere dominance for Chinese character processing, providing evidence for one part of our model.

1. Introduction

The human brain consists of two anatomically different and functionally complementary hemispheres, though the two hemispheres are similar in overall appearance. The two hemispheres complement each other for most functions, including language. Functional lateralization seems to be an ingenious strategy that developed over the time course of human evolution to make the best use of brain capacity (Delis, Robertson, & Efron, 1986; Ivry & Robertson, 1999; MacNeilage, Rogers, & Vallortigara, 2009). For instance, the left hemisphere (LH) processes preferentially relatively local and routine/sequential behavior, while the right hemisphere (RH) processes global and holistic behavior (MacNeilage et al., 2009). Such lateralization preferences may increase processing speed by avoiding longer pathways, mainly via the corpus callosum, that would otherwise be needed to connect regions on opposite sides of the brain (Gazzaniga, 2000). Also, when two homologous areas on opposite sides of the brain perform two different functions, the brain's cognitive capacities are in a sense doubled. Rogers, Zucca, and Vallortigara (2004) discovered that normally developed (strongly lateralized) chicks could simultaneously perform a dual task: the chicks had to find grains scattered among pebbles, a LH task, while they monitored for the appearance of a model predator overhead, a RH task, but chicks that had developed abnormally by incubating their eggs in the dark (weakly lateralized) could not attend to two tasks simultaneously.

As for language, current evidence shows that, for right-handed monolinguals, the LH is generally more functionally specialized for language than the RH (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Gazzaniga, 1970; Hellige, 1993; Leehey & Cahn,

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1979; Searleman, 1977; Soares & Grosjean, 1981; Wada, Clarke, & Hamm, 1975). LH dominance of language does not mean that the RH is totally absent for language processing. The two cerebral hemispheres always communicate closely, mainly via the corpus callosum. Furthermore, the cortex exhibits great plasticity, by which the malfunction of some brain regions can be compensated by homologous regions in the opposite hemisphere. Findings from healthy subjects and patients who underwent callosotomy or who experienced unilateral brain damage all provide converging evidence of compensatory hemispheric function in language (Hickok & Poeppel, 2007; Taylor & Regard, 2003).

While LH dominance for language is widely accepted for right-handed monolinguals, the hemisphere lateralization patterns for bilinguals are much more controversial. Hull and Vaid (2007) have analyzed 66 behavioral laterality studies and found that early bilinguals, who acquired both languages no later than age 6, showed bilateral hemisphere involvement for both languages, while monolinguals and late bilinguals, who acquired their second language after age 6, showed LH dominance for the languages. Yip and Matthews (2007) provide a fine-grained longitudinal study of early bilingualism acquired in a naturalistic setting. It is possible that the age 6 is an important threshold during the ontogenetic development of the brain. At age 6, the brain has reached more than 90% of its adult volume/weight and is four times its birth size (Courchesne et al., 2000; Lenneberg, 1967). From age three to six, extensive internal neuron wiring and synapse pruning (as wiring is eliminated based on the "use it or lose it" principle) take place in the frontal lobes, the cortical regions involved in organizing actions, planning activities and focusing attention (Huttenlocher & Dabholkar, 1997). Therefore, it is possible that bilateral, rather than LH-dominant, cortical organization of language is due to the better use of brain capacity for multiple languages by early bilinguals. Moreover, the cortical organization of language can hardly be shifted from one hemisphere to the other after age 6 just because another language is being acquired, leading to late bilinguals becoming more like monolinguals with respect to their first language. This early organization takes full advantage of the period of greatest neural plasticity during early childhood, since language learning is a major task, especially learning two languages simultaneously.

As mentioned above, the two hemispheres preferentially process different kinds of information, with local and routine/sequential behavior dominant in the LH, and global and holistic behavior in the RH (Hsiao, Shieh, & Cottrell, 2008; Ivry & Robertson, 1999). The kind of writing system may differentially demand sequential/local vs. holistic/global processing, and thus plays an important role in hemisphere lateralization when reading words (Dehaene, 2009). Unlike alphabetic writing system such as English, where each word is a series of linearly arranged letters, and letters correspond to phonological segments, the logosyllabic writing system of Chinese does not provide any direct information on phonetic segments (Wang, 1973; Wang & Tsai, in press). Each Chinese character comprises a hierarchical arrangement of strokes, and represents both a morpheme and a syllable simultaneously. Meanwhile, many Chinese characters are complete words, which are called single-character words, such as the color words used in this study.

In fact, more than 80% of Chinese characters are semantic–phonetic compounds, e.g., '红' (red), which consist of two parts: a semantic component, which hints at the meaning of the character, and a phonetic component, which gives a clue to the pronunciation of the character (Lee, Tsai, Huang, Hung, & Tzeng, 2006; Shu, Chen, Anderson, Wu, & Xuan, 2003). The phonetic component does not always predict the pronunciation of the character, e.g., the phonetic component '鬼' (ghost) of '槐' (pagoda tree) is pronounced /gui3/, but the character itself is pronounced /huai2/ (The Mandarin pronunciations of the Chinese characters are represented in Pinyin, and the corresponding lexical tones are represented by Arabic numerals.). Such characters are called irregular characters. There is no way to derive the pronunciation of an irregular character from its phonetic component. Consequently, reading such irregular Chinese characters requires a direct mapping of the whole character to its pronunciation. This situation can be extended to other high frequency (commonly used) regular characters whose phonetic components faithfully represent their pronunciations. Zhou and Marslen-Wilson (1999) found a null decomposition effect for commonly used compound characters, suggesting that reading such characters involves little or no decomposition because the highly efficient processing of the whole characters leaves little time for their phonetic components to be processed sublexically. Converging evidence shows that the processing of commonly used Chinese characters is different from that of low frequency (less commonly used) ones, with faster responses and less demanding procedures for commonly used ones (Kuo et al., 2003). Taken together, the above findings indicate that visual processing of Chinese characters, at least of the commonly used ones, is holistic/global, which is therefore likely to be dominated by the RH.

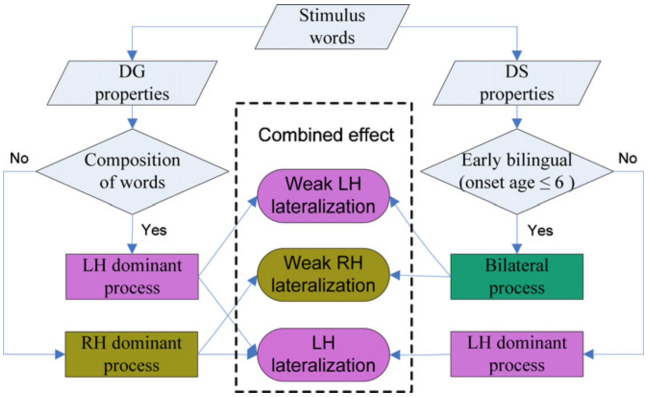

Fig. 1. The CA model of hemisphere lateralization of word reading. DG: domain general; DS: domain specific.

Unlike the reading process of Chinese characters, reading alphabetic words requires performing grapheme–phoneme conversion prior to obtaining the pronunciation of the whole word (Maurer & McCandliss, 2007; Siok, Perfetti, Jin, & Tan, 2004). The requirement of a letter-by-letter grapheme–phoneme conversion leads to a sequential/local scan of each letter. This sequential/local process manner is dominated by the LH. However, unlike graphic processing, language specific processing, such as phonological and semantic processing during word reading of both alphabetic and logosyllabic writings is processed preferentially by the language dominant hemisphere, which is determined by the bilingual status of the participants.

In this study, we first propose a model to predict the lateralization effects in word reading, with focus on Chinese character reading. This model considers both physical (domain general) properties of stimulus words and the bilingual status of participants. Although the model addresses early bilingual, late bilingual, and monolingual, here we test this model using a behavioral Stroop experiment only with late Chinese–English bilingual participants.

2. Model

2.1. Model assumptions

To construct the conceptual model, Composition–Age (CA) model, as depicted in Fig. 1, we use the following two premises:

1. *Composition of stimulus words*: Composition is a synthesizing process in which smaller constituents, e.g., phonemes, are unified into an integrated unit, e.g., the pronunciation of the whole English word. During reading, commonly used Chinese characters (including Chinese single-character words) are visually processed as a whole in order to derive their pronunciations, hence this process is dominated by the RH. In contrast, the visual processing of Chinese multiple-character words and alphabetic words during reading is synthesized, and therefore dominated by the LH.
2. *Age of bilingualism onset*: Age 6 is the threshold between early bilinguals and late bilinguals: early bilinguals acquire both languages by age of 6, while late bilinguals acquire their second language after the age of 6. Early bilinguals process languages bilaterally, while monolinguals and late bilinguals process languages dominantly in the LH.

2.2. *Model description*

Word reading, regardless of the nature (e.g., alphabetic or logosyllabic) of the script, must start with general visual processing. The hemisphere lateralization pattern of processing domain general (DG) properties does not depend on whether the target stimulus is language relevant, but does depend on whether or not the stimulus processing is synthesized, as illustrated in the left part of Fig. 1. If the stimulus is processed constituent-by-constituent, then processing is dominated by the LH, e.g., English words, or else dominated by the RH, e.g., Chinese characters. This DG process focuses on the graphic level. On the other hand, the domain specific (DS) properties, here language-related properties, such as phonology and semantics, are processed in the language dominant hemisphere, which is determined by the bilingual status of participants, as illustrated in the right part of Fig. 1. If the participants are early bilinguals, then these processes have bilateral involvement, otherwise they are dominated by the LH.

The combined/overall lateralization effect of word reading is mainly determined by the lateralization pattern of the DS process, although it can be influenced by that of the DG process, as illustrated in the middle dashed rectangle of Fig. 1. For instance, if the DS process is LH dominant, then the overall lateralization pattern is always LH dominant; if the DS process is bilateral, then the overall lateralization pattern is determined by the lateralization pattern of the DG process, showing a weak LH dominance if the DG process is LH dominant, or a weak RH dominance if the DG process is RH dominant.

This model may only be applicable to languages which are logographic in their writing systems, where intensive visuospatial processing, the earliest stage of reading, is required to recognize the complex structure of the characters (Siok, Spinks, Jin, & Tan, 2009). Therefore, the visual processing may affect the overall lateralization pattern of single Chinese character processing.

2.3. *Model explanatory power*

There are controversies regarding the hemisphere lateralization of Chinese single character processing. Tzeng, Hung, Cotton, and Wang (1979) showed a LVF–RH advantage for commonly used Chinese single characters, and argued that the RH advantage was due to the holistic processing of the overall form of Chinese characters. Similarly, Tsao and Wu found a larger Stroop interference when color words were presented to the LVF (Tsao, Wu, & Feustel, 1981). However, with a similar design as Tsao et al. (1981), Zhang and Peng (1983) discovered an opposite pattern, i.e. LH advantage for Chinese single character processing.

The studies (Tsao et al., 1981; Tzeng et al., 1979) were carried out in USA. Therefore, their participants were possibly early Chinese–English bilinguals. Study (Zhang & Peng, 1983) was carried out in a Chinese environment, Mainland China, so their participants were likely late Chinese–English bilinguals or Chinese monolinguals. By applying the proposed CA model, the hemisphere lateralization pattern of early bilinguals is determined by the nature of the scripts. The holistic process of Chinese characters predicts the RH dominance for Chinese single character reading, which is consistent with the findings in (Tsao et al., 1981; Tzeng et al., 1979). As for the late bilinguals and monolinguals, the strong LH dominance of language processing determines the LH dominance of word reading regardless of the nature of the script, which is consistent with the findings in Zhang and Peng (1983).

We acknowledge there may be other factors in addition to the above two used in the CA model which also influence the lateralization pattern of word reading. Since a secondary verbal interference task was found to modulate language advantage of the language dominant hemisphere in processing language-related tasks (Gilbert, Regier, Kay, & Ivry, 2006, 2008), some studies (Cheng & Yang, 1989; Fang, 1997; Yang & Cheng, 1999) which used a verbal fixation task may not be applicable to the CA model. Moreover, the degree of similarity of the writing systems—both logosyllabic, both alphabetic, or one logosyllabic and the other alphabetic—of the two acquired languages may also play an important role in hemisphere lateralization. We speculate that, if the scripts of the two early acquired languages are of the same type, e.g., both alphabetic, then the overall lateralization pattern will be less or even not influenced by the DG process. This speculation is consistent with the general picture of the bilingual studies surveyed in (Hull & Vaid, 2007). Furthermore, there are biscriptal languages whose writing systems consist of two types of scripts, e.g., syllabic (Kana) and logosyllabic (Kanji) in Japanese. Several studies have found the processing of logosyllabic scripts, e.g., Kanji, is different from that of other types of scripts, e.g., Kana (Coderre, Filippi, Newhouse, & Dumas, 2008; Hatta, 1977; Sasanuma, Itoh, Mori, & Kobayashi, 1977). However, whether the influence of a single biscriptal language and of two early acquired languages on hemisphere lateralization is similar is still not clear. Experimental paradigms, e.g., dichotic listening, half visual field reading, as well as task requirements may also be relevant in this perspective.

2.4. *Model testing*

Given the crossing of neural projections in the visual system, stimuli presented to the right visual field (RVF) are primarily projected directly to the LH, and stimuli presented to the left visual field (LVF) to the RH (Gazzaniga, Ivry, & Mangun, 2002). Therefore, language-relevant stimuli are believed to be processed more efficiently when presented to the RVF than to the LVF for participants whose language functions are dominated in the LH. Thus, language interference is thought to be stronger when language-relevant stimuli are presented to the RVF. This idea has gained support from two lines of research: (1) LH lateralized Whorfian effect: across-category discrimination can be achieved faster in the LH (Drivonikou et al., 2007; Gilbert et al., 2006, 2008; Kay & Kempton, 1984; Kay, Regier, Gilbert, & Ivry, 2009; Siok, Kay, et al., 2009) and (2) LH lateralized Stroop effect: Stroop effects are stronger with words presented to the RVF (Brown, Gore, & Pearson, 1998; MacLeod, 1991; Stroop, 1935).

The Stroop effect refers to the fact that naming a color with congruent language information, e.g., the word "red" written in red ink, is easier and quicker than with incongruent language information, e.g., the word "red" written in green ink. Since the Stroop classic article (Stroop, 1935), research on this well-known effect has developed into a very rich area (MacLeod, 1991). Brown et al. (1998) first summarized the foregoing studies on the lateralization of the Stroop effect, and reported their own results. Their results illustrated stronger Stroop effects when words were presented to the RVF, supporting the hypothesis that more efficient processing of words in the LH will enhance their tendency to produce the Stroop interference.

Based on the above CA model, Chinese single character reading is dominated by the LH for late Chinese–English bilingual participants. We test the hypothesis that the Stroop effect is stronger when stimuli are presented to the RVF than to the LVF since the dominant character reading process in the LH will tend to produce greater interference.

3. Methods

3.1. Participants

Fourteen late Chinese–English bilingual participants (mean age = 24.5 years, *SD* = 2.8), who finished pre-university education in Mainland China, and studied at the Chinese University of Hong Kong when the experiments were performed, were paid to participate in this study. The participants were right-handed, and had normal or corrected-to-normal vision, normal color vision, and proficient in their second language. Informed written consent was obtained from each participant in compliance with a protocol approved by the Survey and Behavioral Research Ethics Committee of the Chinese University of Hong Kong.

3.2. Stimuli

红 (/hong2/, red), 绿 (/lü4/, green), 黄 (/huang2/, yellow), 蓝 (/lan2/, blue) were the four color words used in this study. Three neutral words, 笔 (/bi3/, pen), 表 (/biao3/, watch), and 球 (/qiu2/, ball), and four color patches were used as filler materials. The three neutral words shared no orthographical, phonological or semantic relationship with the above four color words. Each word was represented in four colors, resulting in $(7 \times 4 + 4 \text{ color patches}) \times 2$ visual fields = 64 stimuli. The visual angle of the stimuli was approximately 4.25°, and the width and height of the colored words and color patches were approximately 1.6°, with a viewing distance of 80 cm.

3.3. Procedure

Each trial began with a central fixation '+' for 500 ms. Then, the fixation was replaced by a blank screen for 500 ms. The fixation then reappeared for another 1000 ms, followed by the stimulus screen for 150 ms, an interval selected to reduce eye movements. Participants were instructed to press one of the four color-patch (not color word) labeled buttons (each button corresponded to one designated color) on a PST Serial Response Box (supplied by Psychology Software Tools, Inc., Sharpsburg, PA, USA) to indicate the color of the stimulus that just appeared, and to respond as quickly and as accurately as possible. The subjects were instructed to press the leftmost and second leftmost buttons by the middle finger and index finger of the left hand, respectively, and to press the second rightmost and rightmost buttons by the index finder and middle finger of the right hand, respectively. The number of ipsilateral hand-visual field trials is equal to the number of contralateral hand-visual field trials for each condition. After the response, no feedback was provided, and the screen went blank for 250 ms before the fixation '+' appeared to indicate the start of the next trial. Although participants were instructed to maintain fixation, we did not monitor eye movements.

In some blocks, the participants were instructed to make a vocal response, speaking the name of the stimulus color in participants' native language without pressing a button on the response box—vocal-response trials were otherwise identical to the button-press-response trials described above. Each participant completed three 64-trial button-press-response blocks and three 64-trial vocal-response blocks, with each stimulus used once per block. The order of trials within a 64-trial block was randomized. The block types, button-press-response and vocal-response, were interleaved and the order of the two block types was counterbalanced across participants.

4. Results

The color identification accuracy for both types of responses was very high, with 97% correct responses for button-press response task, and 98% correct responses for vocal response task. Only reaction time (RT) data were analyzed here. Trials in which the participant made wrong responses, or in which the RT fell outside of two standard deviations from the participant's mean were not included in the analysis of the data. Corrections of statistical results for violations of sphericity were made, where appropriate, using the Greenhouse–Geisser method.

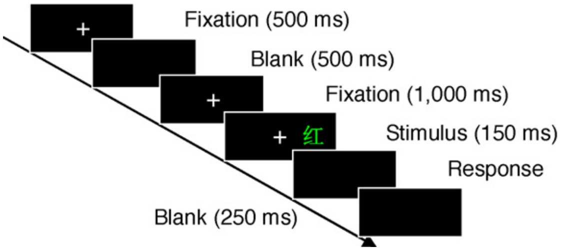

Fig. 2. Illustration of the trial presentation procedure.

Fig. 2 illustrates the procedure for trial presentation, while Table 1 shows the results of RT for the effect of congruency across visual fields, for the two types of responses. The RT data were analyzed using a 2 (*response type*: button-press vs. vocal) × 2 (*visual field*: left vs. right) × 3 (*congruency*: congruent, incongruent, and neutral) within-subject repeated measures ANOVA. There was a highly significant main effect of *congruency*, with congruent condition fastest and incongruent condition slowest [$F(1.23, 15.98) = 43.1$, $p < 0.001$]. There were no effects of *response type* [$F(1, 13) = 2.33$, $p = 0.15$] or *visual field* [$F(1, 13) = 0.1$, $p = 0.76$]. The interaction effect between *response type* and *congruency* was significant [$F(1.3, 17.0) = 9.16$, $p < 0.005$], indicating stronger interference for vocal responses. The interaction effect between *visual field* and *congruency* was significant [$F(1.35, 17.53) = 5.3$, $p < 0.025$], indicating stronger interference in the RVF.

Post hoc comparisons revealed that RT under incongruent condition was significantly longer than that under neutral ($t(13) = 6.79$, $p < 0.001$) and congruent ($t(13) = 6.93$, $p < 0.001$) conditions, and RT under neutral condition was significantly longer than that under congruent condition ($t(13) = 5.21$, $p < 0.001$). Consistent with previous studies on the Stroop effect, the congruent condition shows quickest responses in general, indicating a facilitation effect of congruent language information, while the incongruent condition shows slowest responses, indicating an interference effect of incongruent language information. Under neutral condition, there was a trend showing the RT for vocal response (531 ms) was longer than that of button-press response (505 ms) ($t(13) = 1.6$, $p = 0.068$). Under congruent condition, there was no significant difference in RT between vocal response (488 ms) and button-press response (490 ms) ($t(13) = 0.014$, $p = 0.894$). Under incongruent condition, the RT for vocal response (579 ms) was significantly longer than that of button-press response (527 ms) ($t(13) = 2.9$, $p < 0.01$).

The total Stroop effect (TSE) reflects both a facilitation effect under congruent condition and an interference effect under incongruent condition, and was computed as the RT difference between the incongruent and congruent conditions. Therefore, it represents the total language effect. In order to directly test whether response types and/or visual fields play a significant role in modulating the TSE, the individual TSE data were analyzed using a 2 (*response type*: button-press vs. vocal) × 2 (*visual field*: left vs. right) within-subject repeated measures ANOVA. There were significant main effects of *response type* [$F(1, 13) = 10.7$, $p < 0.01$], with vocal response producing a larger TSE [$t(13) = 3.3$, $p < 0.01$], and *visual field* [$F(1, 13) = 6.76$, $p < 0.05$], with RVF producing a larger TSE [$t(13) = 2.6$, $p < 0.05$] (Fig. 3). There was no interaction effect between *response type* and *visual field* [$F(1, 13) = 0.18$, $p = 0.68$].

The results were consistent with the hypothesis that the Stroop effect was more prominent when stimuli were presented to the RVF than to the LVF. Moreover, different types of responses modulated the magnitude of the Stroop effect, with a stronger Stroop effect for vocal response. However, there was no change to the lateralization pattern. Therefore, the results of this experiment provide evidence for one part of the CA model, the part that is also likely to be applicable to Chinese monolinguals.

Table 1
Mean RT in millisecond and total Stroop effect (TSE) for the effects of congruency across visual fields. The numbers in parentheses were the SEMs.

Congruency	Button-press response			Vocal response		
	LVF	RVF	Average	LVF	RVF	Average
Neutral	498 (26)	512 (26)	505	533 (26)	529 (27)	531
Congruent	501 (28)	479 (28)	490	497 (28)	478 (23)	488
Incongruent	517 (24)	536 (27)	527	575 (33)	582 (30)	579
TSE	16 (14)	57 (17)	37	78 (19)	104 (14)	91

Note: The RT here did not include the 150 ms of stimulus presentation time.

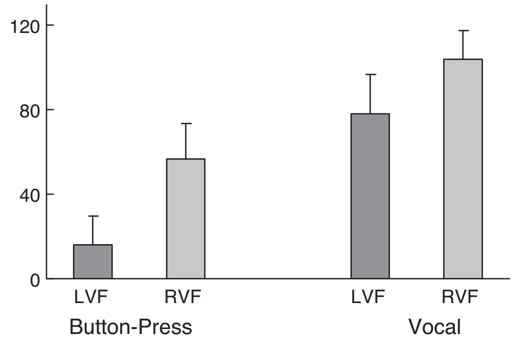

Fig. 3. TSE from 14 participants. Error bars show SEMs.

5. Discussion

The proposed CA model attempts to predict the lateralization of Chinese character reading. The current experimental data show a stronger Stroop effect when Stroop stimuli were presented to the RVF than to the LVF, indicating that word perception of the Stroop stimuli were dominantly processed in the LH for late Chinese–English bilingual participants. Thus, the results of this experiment show that the model accurately predicted lateralization pattern of Chinese character reading for late bilinguals. Given that the cortical organization of the late bilingual is like the monolingual, our findings are likely to be applied equally to Chinese monolinguals. This point favors the idea that processing Chinese single-character words is more functionally lateralized to the LH for late bilinguals and monolinguals.

In addition to the LH lateralized Stroop effect reported here, our data also show that the Stroop effect is stronger for vocal responses than for button-press responses, which is consistent with a survey of the Stroop effect regarding response modality (vocal vs. manual) for western languages (MacLeod, 1991). More specifically, as shown in Table 1, when the language information was neutralized, the RT for vocal response (531 ms) was longer than that for button-press response (505 ms), indicating that vocal response requires more time to be initiated in general. However, congruent language information results in almost the same RT for the vocal response and button-press response (vocal response: 488 ms vs. button-press response: 490 ms). Furthermore, the incongruent language information interfered with the vocal response more than it did the button-press, resulting in significantly longer RT for vocal response (579 ms) than for button-press response (527 ms). Taken together, the vocal response produced a significantly larger Stroop effect than button-press response. Nakamura, Dehaene, Jobert, Le Bihan, and Kouider (2007) showed stronger coupling strength for vocalization in a word repetition task. It is also likely that the stronger Stroop effect for vocal response was due to a similar reason: the stronger coupling between the word perception embedded in the Stroop task and the word production task for vocal response.

To sum up, the current Stroop experiments provide evidence for one part of the CA model. However, we also note that the number of words used in the Stroop paradigm is highly limited, and thus the results may not be conclusive for the hemisphere lateralization of Chinese single character processing by merely using Stroop tests. However, the CA model can be directly tested by future laterality studies on Chinese word reading with various setups: with subjects of both early Chinese–English bilinguals and late Chinese–English bilinguals, with more stimuli of both regular and irregular Chinese characters, with stimuli of both Chinese single-character words and multiple-character words. Consequently, it may be enriched, thereby improving its explanatory power. Moreover, since the bilingual status of participants plays an important role in hemisphere lateralization, we would like to appeal to colleagues here that future studies on language lateralization should clarify the bilingual status of their participants.

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