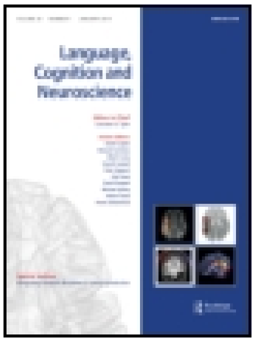

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# Examining radical position and function in Chinese character recognition using the repetition blindness paradigm

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**ABSTRACT**

Repetition blindness (RB) is the failure to report the second occurrence of repeated items in a rapid serial visual presentation stream. The two-stage model of RB [Bavelier, D. (1994). Repetition blindness between visually different items: The case of pictures and words. Cognition, 51, 199–236. doi:10.1016/0010-0277(94)90054-X] states that more properties shared between the repeated items lead to a larger RB effect. We used RB paradigm to examine the position (left or right) and the function (semantic or phonetic) of radicals in Chinese character recognition. Compared to the repeated radicals with the same position and function, RB was reduced when they were in different positions (Experiment 1A), but not when they had different functions (Experiment 1B). Similar RB-effect was observed when only one, or both, of the repeated radicals provided valid semantic or phonetic cues to characters (Experiments 2A and 2B). These results suggest that radicals are encoded with position but not function information. The radical function is likely implemented in lateral connections between semantic and phonological representations of characters.

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Reading; orthography; semantic; phonetic; lexical access

## Introduction

How readers can rapidly recognise Chinese characters is one of the key topics of understanding reading Chinese script (e.g. Chen & Yeh, 2015; Zhou, Ye, Cheung, & Chen, 2009). Two contrasting views of Chinese character recognition have been debated over the past decades. The fact that each Chinese character has a similar size and corresponds to one syllable and one morpheme (DeFrancis, 1989) leads to the *holistic processing view*: a character is a basic processing unit that is not able to be further decomposed (Chen, 1984; Chen & Liu, 2000; Cheng, 1981; Chua, 1999; Hoosain, 1991; Yu, Cao, Feng, & Li, 1990). But Chinese characters have a complex internal structure, suggesting an alternative *analytic processing view*: about 70–80% of traditional Chinese characters belong to the type called phonograms (形聲字) that consist of two radicals (Liu, Su, & Chen, 2001; see Figure 1 for an example). A radical is formed by a group of strokes (such as dots, lines, and curves) and recurs in various characters (Taft & Zhu, 1997). Take the phonogram 楓 ([feng1], "maple") for example. It contains two radicals at different *positions*: 木 on the left and 風 on the right. In addition, the two radicals carry different *functions*: the radical 木 ([mu4], "tree") conveys the semantic category, and the radical 風 ([feng1], "wind") provides a phonological cue to the whole character. Accordingly, 木 is the semantic radical (部首) and 風 is the phonetic radical (聲旁) of the character 楓 (Zhou et al., 2009). Further evidence has demonstrated that radicals are likely the processing unit in recognition of Chinese characters (e.g. Chen & Yeh, 2015; Fang & Wu, 1989; Feldman & Siok, 1997; Taft & Zhu, 1997).

In the present study, we aim to examine whether a radical's position, and/or its function, is encoded during the processing of Chinese character recognition using the repetition blindness (RB) paradigm. RB is a novel method useful to show radical representations in the orthographic processing of Chinese character (e.g. Chen & Yeh, 2015). It is also a well-established method to examine the early stages of orthographic, phonological, and morphemic processing of English words (e.g. Bavelier, Prasada, & Segui, 1994; Harris & Morris, 2001a). Based on the results from the RB paradigm, we would be able to further unearth any orthographic processing rule that is universal by comparing the results of radical representations observed in the present study to our current understanding of sublexical representations in English.

Specifically, previous research has demonstrated that sublexical units such as letter clusters or morphemes (e.g. *er* in the word *worker*) serve as *orthographic* mediators to

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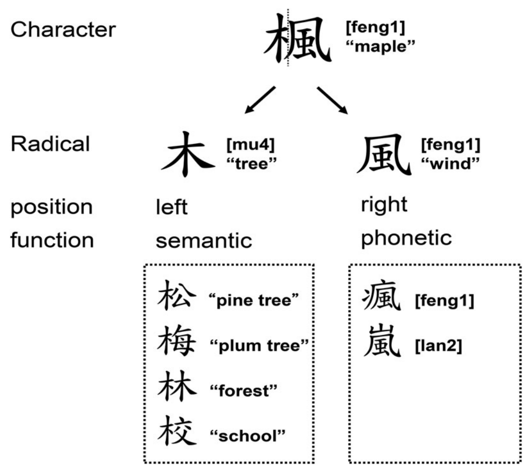


**Figure 1.** An example of phonogram "楓" which consisted of semantic radical "木" on the left and phonetic radical "風" on the right. Some characters sharing the same semantic radical or phonetic radicals are listed.

access lexical representations; in addition, these representations are *position-sensitive* (*er* should be a suffix rather than a prefix, see Crepaldi, Rastle, & Davis, 2010; Harris, 2001; McCormick, Brysbaert, & Rastle, 2009). However, it is still under debate whether morphemes genuinely provide *semantic* information for lexical access; that is, whether transparent morphemes (e.g. *er* in work*er*), as compared to opaque morphemes (e.g. *er* in *corner*), can facilitate visual word processing (see Dunabeitia, Perea, & Carreiras, 2008; Feldman, O'Conner, & Moscoso del Prado Martín, 2009; though see Davis & Rastle, 2010; Rueckl & Aicher, 2008). In summary, sublexical units in English are represented with orthographic and positional information, while not necessarily represented with semantic information.

## *Radical position*

A radical can appear in different positions within a character. For example, the radical 木 is typically presented on the left (e.g. 松) in a horizontal-structure character; but in other instances, it can also appear on the top (e.g. 杏) or on the bottom (e.g. 呆) in a vertical-structure character. Radical *position* and character *structure* provide orthographic information regarding how radicals are organised to construct a character (Taft, Zhu, & Peng, 1999; Yeh & Li, 2002). For instance, the radicals 口 and 力 can be combined horizontally to form the character 加 ([jia1], "to add") or vertically in the character 另 ([ling4], "another").

Taft and Zhu (1997) demonstrated first that radical representations are position-sensitive. Specifically, participants' reaction time (RT) to discriminate characters from non-characters (known as *character decision task*, CDT, Taft, 2006) was shorter when the characters contained radicals presented at typical rather than atypical positions. In another report, Ding, Peng, and Taft (2004) observed a facilitatory priming effect between characters sharing the same radical only if the radical was at the same position (such as 力 in 功 and 助), rather than at different positions (such as 力 in 功 and 加). According to these results, Taft and colleagues (Taft, 2006; Taft, Zhu, & Ding, 2000) proposed that a radical is encoded with its position information *before* the reader accesses character representations. Specifically, when viewing a character (e.g. 加), strokes activate position-free radical representations first (e.g. 力 and 口); the position-free radical representations are then attached with position tags to form position-sensitive radical representations (e.g. <力 and 口>, < and > label the character boundary), which then activate the character representation.

Character structure constitutes another way to represent radical position. Yeh and colleagues (Yeh, 2000; Yeh, Li, & Chen, 1997, 1999; Yeh, Li, Takeuchi, Sun, & Liu, 2003) demonstrated that Chinese readers categorise characters into five types of structure: in addition to the most common horizontal and vertical structure, there are also L-shaped (e.g. 近), P-shaped (e.g. 床), and enclosed (e.g. 固) structures. Characters that have the same structure are perceived to be more similar than those that have different structures in terms of sorting and visual search performance (Yeh & Li, 2002). Perfetti, Liu, and Tan's (2005) radical spatial representation is similar to the idea of character structure proposed by Yeh and colleagues that Perfetti et al. raised four types of spatial relationships (left–right, top–bottom, close outside–inside, and open outside–inside) to represent the possible configural layouts for radicals to be arranged in a character.

## *Radical function*

Chinese radicals can serve as semantic or phonetic radical in terms of their potential cuing function in a character. In a Chinese dictionary, characters are categorised according to their semantic radicals. Most characters that contain the semantic radical 木, for example, have a categorical meaning related to "tree", such as 松 ("pine tree"), 梅 ("plum"), and 林 ("forest") – such characters are considered *transparent*. Sometimes the cue of a semantic radical can be vague, such as 校 ("school") and such characters are termed *opaque*.

English words sharing all letters except one are called neighbours (such as *gave-have*). Neighbours are "friends" if they have similar sounds (such as *gave-wave*) whereas they are "enemies" if they have different sounds (such as *gave-have*, see Jared, McRae, & Seidenberg, 1990). Similar ideas have been proposed for Chinese characters that contain the same phonetic radical. For example, the phonetic radical 風 ([feng1]) appears in three characters: two of them (楓 and 瘋) have the sound of [feng1] making them *friends*, whereas the pronunciation of the remaining character 嵐 [lan2] is different from the other two, making it an *enemy* to 楓 and 瘋 (Lee et al., 2004; Liu et al., 2001).

The semantic and phonetic radical in each character are often explicitly taught in elementary schools in order to facilitate the learning of new characters. The fact that semantic and phonetic cues are provided by separate parts within a character (i.e. different radicals) presents a unique property of Chinese.

Chen and Allport's (1995) study is perhaps the first one reporting that a Chinese reader's performance is modulated by the function of radicals: Chinese readers in this study attended to semantic radicals in a character semantic matching task and attended to phonetic radicals in a character sound matching task. Feldman and Siok (1997) demonstrated that the combinability of a radical (the number of characters that contain a given radical) in terms of either serving as semantic or phonetic radical, is a critical modulating factor for participants' performance in CDT. Other studies have focused on either the transparency of semantic radicals (Chen & Weekes, 2004; Feldman & Siok, 1999a, 1999b; Leck, Weekes, & Chen, 1995; Li & Chen, 1999; Yan, Zhou, Shu, & Kliegl, 2012) or the cuing validity of phonetic radicals (Fang, Horng, & Tzeng, 1986; Lee, Tsai, Su, Tzeng, & Hung, 2005; Lee et al., 2004, 2007; Liu, Chen, & Sue, 2003; Shu, Anderson, & Wu, 2000; Shu & Wu, 2006; Tsai, Lee, Tzeng, Hung, & Yen, 2004).

Even though a collection of empirical evidence has been reported thus far, current dominant models of Chinese character processing do not include radical functions. In Taft's (2006) interactive-activation model, for example, radical-level representations have position tags but no function tags. The meaning and sound of a character are only accessed through a concept unit (*lemma*), which in Taft's model is activated by the orthographic representation of a character (see also Taft, 2003). Similarly, in Perfetti et al.'s (2005) computational model, radicals are simply orthographic inputs; the meaning and sound of a character would have to be accessed through the orthographic representation of the character. One of the difficulties of deconstructing radical function in such models is that, unlike radical position being a physical property (e.g. it appears on the left or right side of a character), radical function appears to be an abstract taxonomy without obvious determinant rules.

The debate on whether radicals are represented with position or function information was first raised by Taft and Zhu (1997) and Feldman and Siok (1997): specifically, Taft and Zhu (1997) demonstrated that radical position was responsible for influencing participants' performance in a CDT; but Feldman and Siok (1997) argued that, in Taft and Zhu's (1997) design, radical position was confounded with radical function, and the latter was the main factor determining the participants' performance in a CDT. Surprisingly, these two factors were never examined together in a single study. Hence in the present study using the RB paradigm, we hold either position or function of a radical constant while manipulating the other factor to address the debate.

### *The RB paradigm*

RB is the failure to report the second occurrence of repeated items in a rapid serial visual presentation (RSVP) stream (Kanwisher, 1987). In a RB task, for example, the sentence "It was *lunch* time so *lunch* had to be served" is presented word by word in RSVP, and the participants were asked to report all of the words. The occurrence of RB refers to the instance when the sentence was misreported as "It was *lunch* time so had to be served", even though the omission of the repeated word "lunch" leads to an ungrammatical sentence. Given that the RSVP is designed to provide a simplified but well-controlled situation to study people's rapid processing of a series of words (i.e. the identification task in RSVP, Forster, 1970; Gilbert, 1959), the RB phenomenon therefore demonstrate a common deficiency of visual system when reading (see Bavelier et al., 1994).

According to the token individuation hypothesis (Kanwisher, 1987), each item presented in RSVP not only activates a corresponding type node, but also has a token representation associated with it. "Type node" is a pre-existing representation used for recognition, analogous to the "what" in semantic memory. The token is a spatiotemporal representation of an event, analogous to the "where and when" in episodic memory. In order to successfully report a visual event, the activated type has to link to its token. RB results from the limitation that when a given activated type has already linked to a token, it interferes with the establishment of the type linking to a second token, causing "blindness" to the repeated item (see Morris, Still, & Caldwell-Harris, 2009 for a review and a recent comprehensive model for RB).

Bavelier (1994, 1999) further elaborated on Kanwisher's token individuation hypothesis and proposed that RB is not only caused by the failure to link a type to two different tokens, but also by the failure to consolidate the types being bound in tokens because only stabilised bound tokens can be encoded in memory. When representations of the repeated items in a RB task (critical item 1 and critical item 2, called C1 and C2 hereafter) share more common properties (i.e. C1 and C2 have less information to be distinct from each other), the token associated with C2 is less likely to be consolidated and hence RB is more likely to occur (as reflected by a larger magnitude of RB). This is evidenced by the result that RB is larger for two identical words (or two identical pictures) than for a word and a picture referring to the same object, since both visual features and meaning are the same in the former case, while only the meaning is the same in the latter (Bavelier, 1994, Experiment 3). This two-stage model (including *tokenization* and *consolidation*) considers the RB effect as a gradient phenomenon that is determined by the degree of similarity between C1 and C2.

The RB paradigm has been demonstrated to be a useful tool to examine the orthographic, phonological, and semantic representations of English words. For example, RB occurs not only for identical words (such as *lunch-lunch* in the first example), but also for orthographically different words with the same sound (such as *ate-eight*), an effect called phonological RB (Bavelier & Potter, 1992). Furthermore, Semantic RB effect has been reported between synonyms in different languages (e.g. English and Spanish in proficient bilinguals; see MacKay & Miller, 1994; though see Altarriba & Soltano, 1996). On top of that, semantic priming effect (e.g. Neely, 1991) has also been reported under the RB paradigm as well: when a semantically related cue of repeated item was presented before the repeated item (such as *pans-pots-pots* with other filler words in between), the RB effect can be ameliorated (O'Reilly & Neely, 1993; Parasuraman & Martin, 2001). Taken together, the RB effect is susceptible to the orthographic, phonological, and semantic processing of English words when a common (or related) representation(s) is accessed.

The RB paradigm has also been utilised to investigate the internal representations of letter clusters in English words: when presenting the word list *town-wallet-rocket-colony* one-by-one in RSVP, participants sometimes reported the second and third words as *wallet-rock*, where the repeated letter cluster *et* in *rocket* was missing (Harris, 2001; Kanwisher & Potter, 1990). Further examination of letter-cluster RB effect (such as the two-letter cluster *et* in the above example) demonstrated that letter clusters are position-sensitive representations (Harris, 2001); however, letter-cluster RB effect was neither modulated by whether the letter cluster constitutes a morpheme, nor by whether the letter cluster were pronounced regularly (in terms of grapheme-to-phoneme correspondences rules; see Bavelier et al., 1994; Harris & Morris, 2001a). These results suggest that letter clusters merely serve as orthographic inputs that are intermediate between letter and word levels, which is consistent with the findings of recent studies suggesting that the decomposed morphemes at an early stage are simply "morpho-orthographic" units (e.g. Davis & Rastle, 2010; Marslen-Wilson, Bozic, & Randall, 2008; Rueckl & Aicher, 2008; though see Dunabeitia et al., 2008; Feldman et al., 2009).

Given that the RB paradigm has been demonstrated to be a useful tool to examine the internal representations of sublexical letter clusters in English words, we therefore consider it suitable to examine the position and function of radical representations in Chinese character processing as well. Radical-RB effect in Chinese characters was first reported by Yeh and Li (2004; see also Chen & Yeh, 2015). For example, when C1 and C2 were two characters, such as 誠 and 諸 which share a common radical (the left radical "言"), participants were likely to report C2 as 者 or 賭, either omitting the repeated radical of C2, or replacing it with another radical (e.g. 貝) and reporting an incorrect character, 賭.

Chen and Yeh (2015) recently demonstrate that RB is a sensitive paradigm to study early orthographic processing of Chinese characters: the radical-RB effect can be observed in characters in a wide range of frequencies. In contrast, in CDT – a commonly used method to study Chinese character processing – radical effects were only observed in low-frequency, rather than in high-frequency characters (e.g. Ding et al., 2004; Li & Chen, 1999; Wu & Chen, 2003). Furthermore, radical-RB effect has been verified as occurring at radical-level representations, rather than a sort of character-level inhibition due to overall similarity given the following reasons: first, the radical-RB and character-RB effects can be dissociated in terms of their time course, and critically, it was earlier for radical-RB effect (Yeh & Li, 2004). Second, the radical-RB effect was reduced with longer presentation time of C1 (Chen & Yeh, 2015, Experiment 1). This pattern is consistent with the sublexical RB (Harris & Morris, 2001b) rather than lexical inhibition in English (Chialant & Caramazza, 1997). Third, radical-RB effect was not susceptible to the proportion of the repeated radical within in a character (i.e. similarity at the character level determined by the number of overlapped strokes, see Chen & Yeh, 2015, Experiment 2). Finally, Chen and Yeh (2015) reliably observed explicit radical-RB effect (i.e. repeated radical was omitted or replaced whereas the non-repeated radical was reported) by analysing the participants' error patterns. Combining these previous results, we believe that the radical-RB is an ideal paradigm to examine the representation of radicals.

## Overview of the experiments

We used the RB paradigm to examine whether radicals are encoded with their position and/or function. Bavelier's (1994) two-stage model was adopted to assess the effect: radical representations sharing more properties lead to a larger RB effect. In Experiment 1A, we manipulated the position of repeated radicals as same or different while keeping their function the same (either both semantic or both phonetic radicals); in Experiment 1B, we manipulated the function of the repeated radicals as same or different while keeping their position the same (either both on the left or both on the right, see Yeh & Chen, 2002, for a similar design). The hypothesis is that, if radicals are represented by their position (or function), radical-RB effect would be larger when the repeated radicals have the same position (or function).

In order to further explore the functional role of radicals, in Experiment 2 we manipulated whether both repeated radicals fulfil their designated function (i.e. providing valid semantic or phonetic cue to the character). If semantic radicals truly convey the meaning of a character during recognition, the RB effect should be larger for repeated semantic radicals when both C1 and C2 are transparent (i.e. the semantic cue is valid in both characters) than when one is transparent and the other opaque (i.e. the semantic cue is only valid in the former but not in the latter). Similarly, if phonetic radicals truly convey the sound of characters, the RB effect should be larger for repeated phonetic radicals when C1 and C2 are friends (i.e. the phonetic radical provides the same cue to both characters) than when C1 and C2 are enemies (i.e. the phonetic radical provides the different cues to each character). These two hypotheses were tested in Experiments 2A and 2B, respectively. Finally, we discuss the implications of our results for currently available Chinese character processing models.

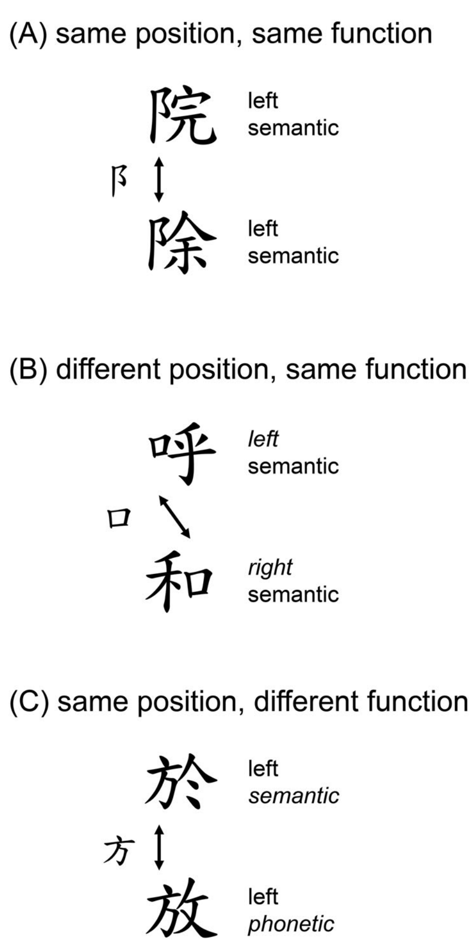


**Figure 2.** Example of C1 and C2 used in Experiments 1A and 1B. (a) Characters share the radical having the same position and function; (b) characters share the radical having the same function but locating at different positions; (c) characters share the radical having the same position but serving different functions.

## Experiment 1A: radical position manipulated

In this experiment, we compared the RB effects for repeated radicals with the same function and position (e.g. 院-除, see Figure 2(a)) and for those with the same function but located at different positions (e.g. 呼-和, see Figure 2(b)). If radical position is represented, then the RB effect should be larger when the repeated radicals are at the same position than at different positions.

### *Method*

#### *Participants*

Sixty undergraduate students at National Taiwan University (NTU) participated in the experiment in exchange for course credit. All of them were native Mandarin Chinese speakers, and had normal or corrected-to-normal vision by self-report. They were naïve regarding the goal of the study. The protocol was approved by the ethical committee in the Department of Psychology, NTU.

#### *Stimuli and design*

Stimuli were displayed on a 15-inch color-calibrated monitor with a refresh rate of 70 Hz controlled by a personal computer. Participants sat at a viewing distance of 60 cm in a dimly lit chamber. All of the visual stimuli were presented in white in the centre of a black background. The RSVP sequence consisted of seven items including four symbols and three characters (Figure 3). Each item was presented at a rate of 43 ms/item in the order of S, S, IR, C1, S, C2, and S (S: symbol; IR: irrelevant character; see Yeh & Li, 2004). In order to avoid any undesirable priming effect, the three characters did not have obvious semantic relationships, and the concatenation of their pronunciations did not sound like any two- or three-character word. They did not share the same syllables, nor did they rhyme.

C1 and C2 were different in both font and size in order to avoid the possibility that the repeated radicals would visually merge (e.g. Harris, 2001; Morris & Harris, 1999). IR and C2 were in the Chia font (楷體, 1.15° × 1.24°, width × height) and C1 was in the Fang font (方體, 1.53° × 1.43°). C1 and C2 were characters with horizontal structure (such as 院, the radical 阝 is on the left and the radical 完 is on the right), while IR was a character with vertical structure (such as 星, the radical 日 is on top of the other radical 生). The 4 symbols were selected randomly without replacement from a set of 30 symbols, including &, ▽, ≒, $, etc., subtended from 1.21° × 0.80° to 1.43° × 1.24° (see Appendix 1). The beginning and the end of a RSVP stream were signalled by a fixation cross (1.15° × 1.24°).

Three within-subject factors were manipulated: *Position* (same or different), *Function* (semantic or phonetic), and *Radical Repetition* (repeated or unrepeated). Given that C1 and C2 were horizontal characters in the present study, the repeated radicals in C1 and C2 were both on either the left or right side in the same-position condition, and on the left in C1 and on the right in C2 (or vice versa) when in the different-position condition. For the factor of Function, the repeated radicals in half of the trials were semantic radicals and in the other half, phonetic radicals (Appendix 1, (1) and (2)). The semantic radicals were obtained from a Chinese dictionary published by the Ministry of Education in Taiwan (2000). In addition, we double checked with four other dictionaries commonly used in Taiwan in order to ensure that all the semantic radicals we chose in this study are defined consistently by all five dictionaries.[1] All phonetic radicals used in the present study were listed in a manual of phonetic radicals (Liu et al., 2001).

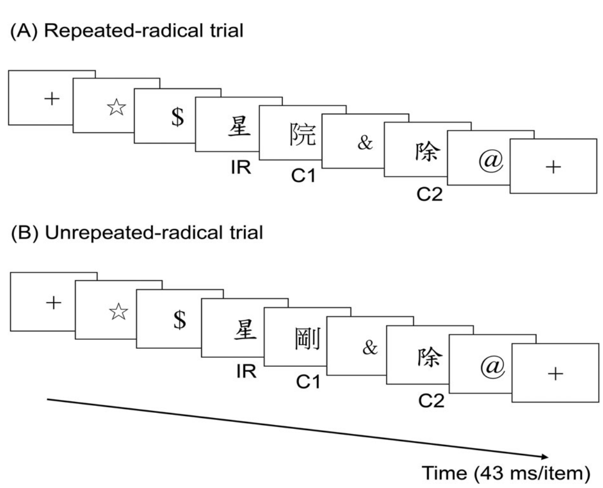


**Figure 3.** The sequence of the RSVP used in the current study. (a) An example of the repeated-radical trial that C1 (院) and C2 (除) share the radical 阝. (b) An example of the unrepeated-radical trial. The only difference is that C1 is replaced by a different character (剛) without sharing any radical. IR: irrelevant character; C1: critical item 1; C2: critical item 2.

For each of the Position × Function conditions, a list of 14 characters was first selected as C2. Character frequency (according to Tsai, 1996) and stroke counts of C2s were matched in these four conditions. The values were submitted to two-way analysis of variances (ANOVAs) and none of the effect was significant (all *F*s < 1, *p*s > .5). Each C2 was paired with 2 types of C1s: In the repeated condition, 14 characters sharing one repeated radical with C2 were selected. In the unrepeated condition, 14 characters not sharing any radical with C2 were selected. Both the character frequency and the stroke counts of C1s in the repeated and unrepeated conditions were matched (three-way ANOVA of Position × Function × Radical Repetition, all *F*s < 1.75, *p*s > .1). The factor of Radical Repetition was counterbalanced across participants in a yoked design. That is, two versions were constructed so that, in each version, a given C2 was only presented once and was paired with either repeated or unrepeated C1.

Using this design, in the different-position condition, either C1 or C2 had the repeated radical appear in its typical position (i.e. semantic radical on the left and phonetic radical on the right). For example, the repeated semantic radical 口 in 呼 and 和 appears in its *typical* position (left) in C1 (so C1 is the typical character and C2 is atypical), while the repeated phonetic radical 工 in 攻 and 江 appears in its *typical* position (right) in C2. In order to prevent confounding the RB effect with the presentation order of typical and atypical radical position of a character, we counterbalanced the typical radical position in C1 or C2 across participants. Hence, half the participants saw the repeated radical appear at its typical position in C1, and the other half, at its typical position in C2 (i.e. the order to present C1 and C2 were swapped in these two conditions).

An additional group of filler trials, which illustrated the occurrence of radical-RB, comprised one-third of the trials in the experiment. There was one filler trial, for example, with 眨 and 分 as C1–C2 that could have been the result of radical-RB of the second 目 in 眨 and 盼. Adding such filler trials served to reduce the proportion of trials containing repeated radicals in the experiment. In addition, adding filler trials helped reduce the likelihood that participants strategically filled a radical even when they did not see it, which would therefore prevent a potential underestimation of radical-RB effect. There were 84 trials in total (7 trials × 2 Position × 2 Function × 2 Radical Repetition conditions + 28 filler trials), presented in a completely randomised order for each participant.

### *Procedure*

Participants initiated a trial by pressing the space bar. A tone was presented for 150 ms to signal the start of a trial, and followed by a fixation cross for 500 ms before the RSVP sequence was presented. Participants were asked to write down all of the three characters they saw in each RSVP stream. They were encouraged to guess if not certain, but no feedback was given. In the practice session, they conducted seven unrepeated trials using characters that were not used in the main experiment. If a participant failed to report all three characters for three trials, the practice session would be rerun. This time the participant reported the characters orally, and the experimenter made sure that he or she had followed the instructions and had seen the three characters presented in each trial. Less than 10% of the participants failed the first practice session, and no one failed the second one.

### *Results and discussion*

In all the experiments in this study, a trial was counted as accurate only when both C1 and C2 were correctly reported, regardless of their order (Kanwisher, 1987; Park & Kanwisher, 1994). The accuracy data were analysed using logit mixed model (see Jaeger, 2008) in the lme4 package (Bates et al., 2015, version 1.1-8) in R (version 3.2.1). The fixed factors were Position, Function, and Radical Repetition (Figure 4(a)), and the random factors were Subject and Trial.[2]

The results revealed that the main effect of Radical Repetition was significant: a significant radical-RB effect was found, as evidenced by higher accuracy in the unrepeated than in the repeated condition (68.1% vs. 52.1%, $z = 2.87$, $p < .005$). The main effect of Position was also significant with higher accuracy in the different than in the same position (62.4% vs. 57.9%, $z = 1.96$, $p < .05$). The two-way interaction of Radical Repetition × Position was significant ($z = 3.12$, $p < .005$), indicating a larger radical-RB effect when the radicals were located at the same position than when they were at different positions (25.2% vs. 6.7%, $t(59) = 5.67$, $p < .001$). No other main effect or interaction was significant.

In Experiment 1A, the position of the repeated radicals was either same or different while their function was held constant. The results revealed that when the repeated radicals appeared at the same position, the radical-RB effect was robustly observed (see also Chen & Yeh, 2015). Critically, the magnitude of radical-RB was larger when the repeated radicals appeared at the same position than at different positions. This result suggests that a radical and its position information are represented together, leading to a higher similarity (and thus a larger magnitude of RB) between radicals that are in the same position.

In an orthographic priming study, Ding et al. (2004) demonstrated that the facilitatory priming effect was larger when prime and target characters shared a radical at the same position. Even though radical-RB (an inhibitory effect) and orthographic priming (a facilitatory effect) are effects in different directions, both results suggest that radicals are more similar when located at the same position than at different positions. The result of Experiment 1A therefore provides supporting evidence for the multi-level interactive-activation model (Taft, 2006) which emphasises the importance of radical position in Chinese character processing.

## Experiment 1B: radical function manipulated

Experiment 1B was designed to compare the RB effects for repeated radicals that have the same function and position (e.g. 院-除, Figure 2(a)) vs. those located at the same position but having different functions in C1 and C2 (e.g. 於-放 Figure 2(c)). If radical function is represented, then the RB effect should be larger when the repeated radicals have the same function than when they have different functions.

### *Method*

### *Participants*

Another group of 60 undergraduates studying at NTU participated in this experiment.

### *Stimuli and design*

The following three within-subject factors were manipulated: *Function* (same or different), *Position* (left or right), and *Radical Repetition* (repeated or unrepeated). Note that we used the same set of characters in the same positions and the same-function conditions from Experiment 1A in this experiment in order to be able to compare the results in the two experiments. Half the repeated radicals had the same function. In each function condition, half of them were repeated on the left and the other half on the right (Appendix 1, (1) and (3)). Character frequency and stroke counts of C2s were matched (two-way ANOVA of Function × Position, all $Fs < 2.37$, $ps > .1$), and so were those for C1s (three-way ANOVA of Function × Position × Radical Repetition, all $Fs < 2.68$, $ps > .1$). Again, the repeated radical being presented at its typical position in either C1 or C2 was counterbalanced across participants. Other details were identical to those in Experiment 1A.

### *Results and discussion*

A logit mixed model was conducted on the fixed factors of Function, Position, and Radical Repetition (Figure 4(b)).[3]

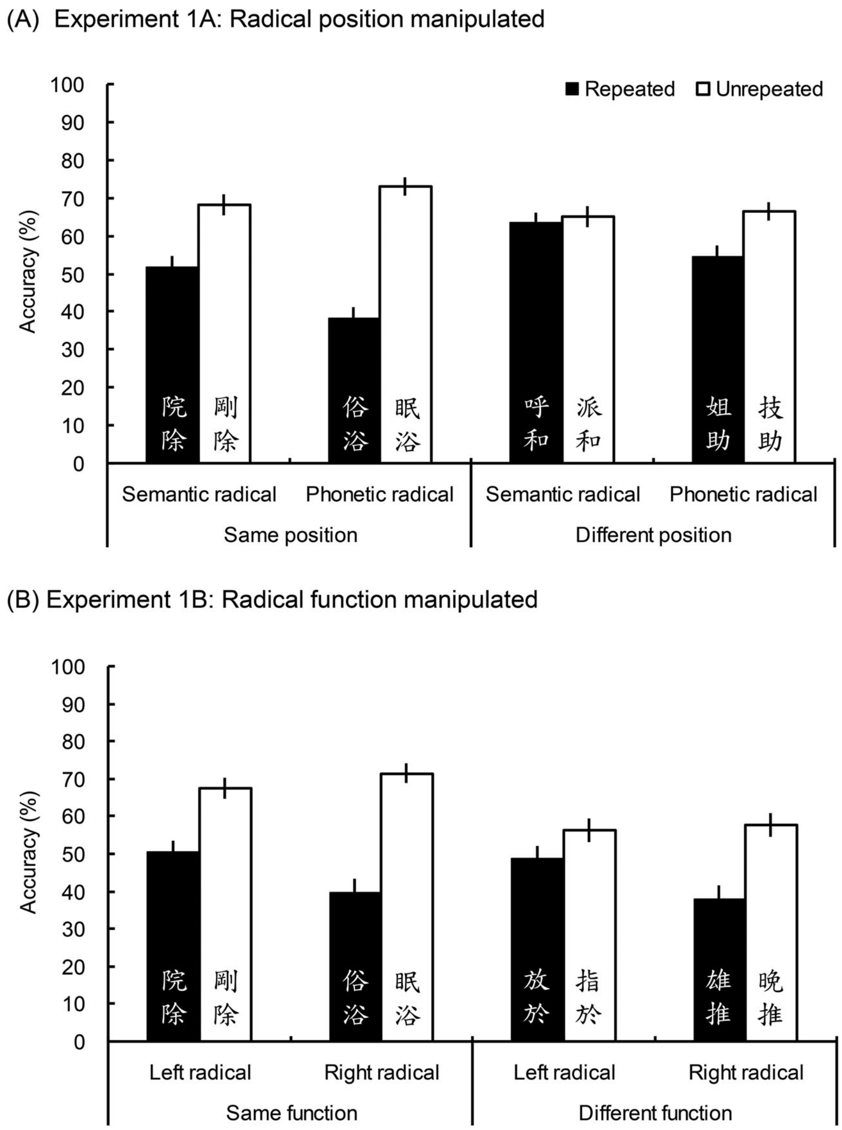


**Figure 4.** Mean accuracy of participants' character identification performance in Experiments (a) 1A and (b) 1B. The error bars indicate ±1 standard error of the means.

Only the main effect of Radical Repetition was significant: a significant radical-RB effect was observed given the higher accuracy in the unrepeated than in the repeated condition (63.2% vs. 44.4%, $z = 2.24$, $p < .05$). Unlike Experiment 1A, the critical interaction between Radical Repetition × Function was not significant ($z = 1.90$, $p = .06$).

We further compared the reduction of the radical-RB magnitude due to either changing position (Experiment 1A) or changing function (Experiment 1B). When changing position, the radical-RB effect was reduced by 18.5% (from 25.2% to 6.7%); when changing function, the radical-RB effect was reduced by 11.0% (from 24.3% to 13.3%). The reduction of the radical-RB effect was larger when changing position than when changing function ($t(118) = 1.72$, $p < .05$, one-tailed).

In Experiment 1B we manipulated the function of the repeated radicals (either same or different) while keeping their positions constant. There was no significant difference for the magnitude of radical-RB whether the repeated radicals had the same function or not, suggesting that the radical is unlikely to be represented with its function (i.e. semantic or phonetic) during Chinese character recognition. In addition, the larger radical-RB reduction when changing position rather than changing function suggests that radical position is more clearly encoded than radical function.

### Discussion of Experiment 1

The question of whether radicals are represented by position (left or right) and/or function (semantic or phonetic) was examined in Experiments 1A and 1B. The results demonstrated that the radical-RB effect was larger when the position and function of repeated radicals were the same as compared to when only the position of the repeated radicals was changed. The radical-RB effect was similar when the position and function of repeated radicals were the same as compared to when only the function was changed. According to Bavelier's (1994) two-stage model suggesting that the RB effect should be larger when the representations of the critical items share more properties, the reduction of the radical-RB effect attributable to changing position indicates that radicals were represented with position. On the other hand, the absence of significant reduction of the radical-RB effect when the radical function was different suggests that radicals might not be represented with function.

When comparing the results of Experiments 1A and 1B, two patterns further support that Chinese radical was represented with position but not with function. First, the reduction of radical-RB effect due to changing position (18.5%) was more pronounced than when it was due to changing function (11.0%). Second, the reduction of radical-RB effect due to changing position was certainly attributed to the *higher* accuracy in the *repeated* condition in the different-position than in the same-position conditions (see the black bars in Figure 4(a)). The small reduction of radical-RB effect due to changing function, though not significant, was mainly attributed to the *lower* accuracy in the *unrepeated* condition in the different-function than in the same-function conditions (see the white bars in Figure 4(b)), while the accuracies in the repeated trials were similar. Radical identity and position information therefore determined the accuracy in the repeated conditions in Experiment 1B.

Radical position is a concrete feature and radicals can be located either left or right in a horizontal character, or one above the other in a vertical character (e.g. Taft & Zhu, 1997; Yeh & Li, 2002; Yeh et al., 2003). Given that radicals serve as basic orthographic units of Chinese character processing (Chen & Yeh, 2015; Feldman & Siok, 1997; Taft & Zhu, 1997), radical position (or structure) is therefore necessarily represented in order to provide a constraint when radicals are bound to character representations (Perfetti et al., 2005; Taft, 2006; Taft et al., 1999). Radical function, on the other hand, lacks any concrete determinant properties. As demonstrated in the manipulation of the different-function conditions in Experiment 1B (see Figure 2(c)), a radical located at a given position can either be semantic or phonetic in a character.

In addition to examining radical function in categorical terms (i.e. either being semantic or phonetic radical) as in Experiment 1B, radical function may influence Chinese character processing in a more fine-grained fashion. That is, whether a Chinese radical genuinely fulfil its functional role by providing a semantic or phonetic cue to the character – this is how previous studies examined the functional role of semantic and phonetic radicals during Chinese character processing (see the *Radical function* section in Introduction). Accordingly, the functions of repeated radicals were manipulated as follows: in Experiment 2A, either one or both of the repeated *semantic* radicals fulfilled the function. And similarly, in Experiment 2B, either one or both of the repeated *phonetic* radicals fulfilled the function. Following the prediction of the two-stage model of RB, the radical-RB effect should be larger when both radicals fulfil the function.

## Experiment 2A: function of semantic radical manipulated

In Experiment 2A, the function of the semantic radical was manipulated. A semantic radical fulfils its function when its semantic category is congruent with the meaning of the character (i.e. transparent), such as the semantic radical 犭 (dog) in the character 狼 (wolf). Otherwise, a semantic radical does not fulfil its function in a character (i.e. is opaque), such as in the example of the semantic radical 犭 (dog) in the character 猜 (guess).

### *Method*

#### *Participants*

A new group of 48 participants from the same pool as in Experiment 1 took part in this experiment.

#### *Stimuli and design*

We manipulated two factors, *Semantic Function* (same or different function) and *Radical Repetition* (repeated or unrepeated). Twenty semantic radicals were selected from the Chinese Dictionary published by Ministry of Education in Taiwan (2000). For semantic radicals, we chose three characters with similar character frequency and stroke counts, and two of them were transparent characters (one for same-function C1 and the other for C2) and one was opaque (for different-function C1, paired with the same C2 as in the other condition). That is, in the same semantic function condition, the semantic radicals in both C1 and C2 fulfilled the function (i.e. both C1 and C2 are transparent characters); in the different semantic function condition, the semantic radical only fulfilled the function in C2 (i.e. C1 is opaque character and C2 is transparent character). The semantic radicals in all of these characters were on the left.

Another group of 41 participants were asked to rate the transparency of the semantic radicals in these 60 characters using a seven-point scale in which larger numbers indicate higher transparency. The rated means of 40 transparent characters were higher than 4.5, and the rated means of 20 opaque characters lower than 3.5. Each C2 was paired with four kinds of C1: same-function C1, different-function C1, and their unrepeated controls respectively. The character frequency and stroke counts of the four kinds of C1 were matched (two-way ANOVA of Semantic Function × Radical Repetition, all $Fs < 1.27$, $ps > .1$).

In the same-function condition (such as 狼 (wolf) and 狸 (fox)), C1 and C2 were semantically related. However, semantic relatedness in the different-function condition between opaque C1 and transparent C2 (such as 猜 (guess) and 狸 (fox)) was low. Semantic relatedness in the unrepeated condition was accordingly matched in order to be comparable to their repeated condition. In this design, the interaction between Semantic Function and Radical Repetition would be critical to indicate that transparent and opaque semantic radicals are represented differently (e.g. Feldman & Siok, 1999a, 1999b). On the other hand, only a significant main effect of Semantic Function without interaction would suggest an effect elicited by the semantic relatedness between C1 and C2 (i.e. semantic priming effect at the character level).

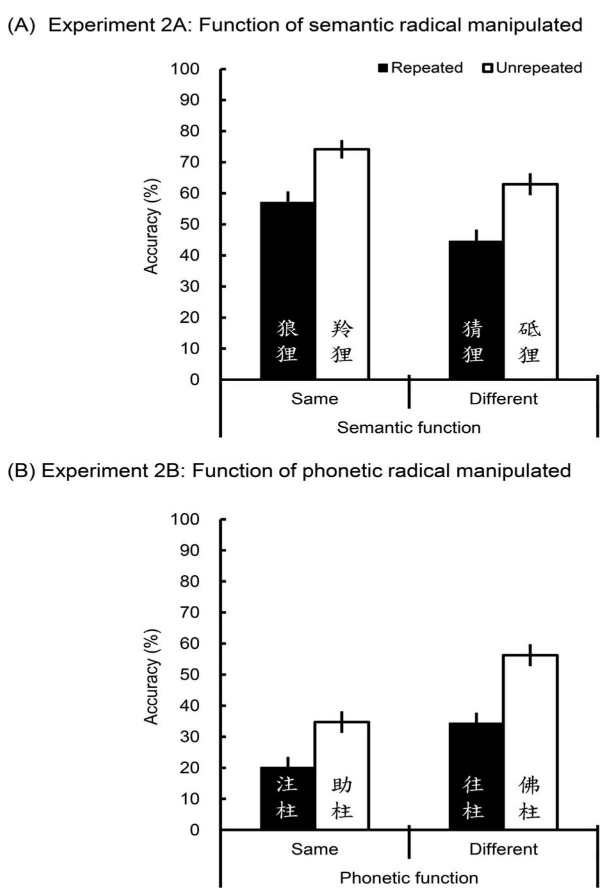


**Figure 5.** Mean accuracy of participants' character identification performance in Experiments (a) 2A and (b) 2B. The error bars indicate ±1 standard error of the means.

Two groups of 24 participants were asked to rate the semantic relatedness of C1 and C2 in the repeated and unrepeated conditions separately; that is, one group rated the list of character pairs that always share a same semantic radical, while the other group rated the list of character pairs that never have the same radical. This was to control for orthographic similarity in order to avoid the possibility that characters sharing the same semantic radical may be rated as more semantically related than those that do not. A seven-point scale where larger numbers represent higher semantic relatedness was used. The mean ratings in the same-function conditions were 5.25 and 5.40 in the repeated and unrepeated condition, respectively, and the values were larger than the mean ratings in the different-function conditions (1.99 and 1.79 in the repeated and unrepeated condition, respectively). The rating results were submitted to a two-way ANOVA. Only the main effect of Semantic Function was significant ($F(1,76) = 1235.25$, $p < .0001$). The other main effect, Radical Repetition, and their interaction were not significant (both $ps > .05$). Therefore, the semantic relatedness between C1 and C2 in the repeated and unrepeated conditions was well matched. The characters used in this experiment are shown in Appendix 2.

The factors of Semantic Function and Radical Repetition were counterbalanced across participants in a yoked design. That is, four versions were constructed and, in each version, a given C2 was only presented once and was paired with C1 in one of the four conditions. Two kinds of filler were presented: the first kind consisted of 12 items that mimicked the occurrence of radical-RB as used in Experiment 1. The second kind consisted of five items, in which C1 and C2 shared a non-character meaningless semantic radical which could not stand-alone as a simple character, such as 彳 and 攵. This aimed to reduce the likelihood that participants realised the transparency between radicals and characters. There were 40 trials (5 trials for each of the Semantic Function × Radical Repetition conditions and 20 fillers) in the main experiment. The procedures and other details were the same as in Experiment 1.

### Results and discussion

The results are shown in Figure 5(a). A logit mixed model on the fixed factors of Semantic Function and Radical Repetition was conducted.[4] The radical-RB effect was significant: the accuracy was higher in the unrepeated than in the repeated condition (68.5% vs. 50.8%, $z = 2.90$, $p < .005$). The factor of Semantic Function was also significant: the accuracy was higher in the same than in the different condition (65.6% vs. 53.8%, $z = 2.34$, $p < .05$). However, their interaction was not significant ($z = 0.60$, $p = .55$). The magnitude of radical-RB was not significantly different between the same- and different-function conditions (17.1% vs. 18.3%, $t < 1$, $p > .8$).

The results demonstrated significant radical-RB effects in both same and different semantic function conditions, and the magnitudes were similar. This result suggests that semantic radicals in a transparent or opaque character plausibly access the same radical representation. This finding is consistent with Feldman and Siok's (1999a, 1999b) results: the orthographic and semantic priming effect between transparent characters (such as 狼 and 狸) was additive when the stimulus onset asynchrony (SOA) between the two characters was 43 ms, the same presentation duration of C1 used in the current study. Feldman and Siok further demonstrated that the interactions between semantic radicals and characters in terms of radical transparency can be observed at longer SOAs (72 or 243 ms, or across trials). Their results suggest that semantic interactions between semantic radical and characters likely occur at a later stage of character processing. Our result is also consistent with the results that RB for letter clusters is insensitive to the morphemic information in English (Bavelier et al., 1994).

The participants' performance was better when C1 and C2 were semantically related (i.e. in the same-function conditions) than when they were semantically unrelated in the different-function condition, suggesting the semantic priming effect between C1 and C2 (e.g. O'Reilly & Neely, 1993; Parasuraman & Martin, 2001). This semantic priming effect demonstrates that the meanings of C1 and C2 have indeed been accessed during the processing of RSVP stream. Nevertheless, the orthographic effect at the radical level (i.e. radical-RB effect) and the semantic effect at the character level (i.e. semantic priming effect) were additive in modulating participants' performance.

## Experiment 2B: function of phonetic radical manipulated

In Experiment 2B, we examined the function of phonetic radicals on the RB effect. The phonetic radical provides "friend" neighbours with the same phonological cue (e.g. 注 and 柱, both are pronounced [zhu4]), while providing different phonological cues to "enemy" neighbours (e.g. 往 [wang3] and柱 [zhu4]).

### Method

#### Participants

A new group of 48 participants from the same pool as in Experiment 1 took part in this experiment.

#### Stimuli and design

Two factors, *Phonetic Function* (same or different function) and *Radical Repetition* (repeated or unrepeated), were manipulated. Twenty-four phonetic radicals were selected in order to fit the criterion that more than half of the characters containing the phonetic radical had the same sound (according to Liu et al., 2001). For each phonetic radical, three characters were chosen as stimulus materials: two of them pronounced the sound in the majority (one for same-function C1 and the other for C2) and one character pronounced different sound (for different-function C1, paired with the same C2 as in the other condition). In the same phonetic function conditions, C1 and C2 are friends (e.g. 注-柱, both are pronounced [zhu4], so they are homophone); in the different phonetic function condition, C1 and C2 are enemies (e.g. 往-柱, pronounced [wang3] and [zhu4]). In order to match the similarity in sound, the unrepeated counterparts in the same-function condition were homophones and the unrepeated counterparts in different-function condition were not. In this design, the interaction between Phonetic Function and Radical Repetition was critical to indicate that friend and enemy phonetic radicals are represented differently. Otherwise, only a significant main effect of Phonetic Function without interaction would suggest an effect elicited by the homophone between C1 and C2 (i.e. the homophone RB). The phonetic radical appeared on the right side in all of these characters.

Each C2 was paired with four kinds of C1: same-function C1, different-function C1, and their unrepeated controls respectively (see Appendix 3 for the stimulus materials). The character frequency and stroke counts for the four kinds of C1 were matched (two-way ANOVA of Phonetic Function × Radical Repetition, all $Fs < 0.73$, $ps > .3$). The factors of Phonetic Function and Radical Repetition were in a yoked design. There were 24 trials, 6 trials for each of the 4 Phonetic Function × Radical Repetition conditions, as well as 16 filler trials simulating the occurrence of radical-RB. Hence, there were a total of 40 trials in the experiment. The procedures and other details were the same as in Experiment 1.

### Results and discussion

The results are shown in Figure 5(b). A logit mixed model was conducted on the fixed factors of Phonetic Function and Radical Repetition.[5] The radical-RB effect was significant that the accuracy was higher in the unrepeated than in the repeated condition (45.5% vs. 27.3%, $z = 2.80$, $p < .001$). The factor of Phonetic Function was also significant with the accuracy higher in the different than in the same condition (45.3% vs. 27.4%, $z = 3.63$, $p < .001$). However, the interaction of Phonetic Function × Radical Repetition was not significant ($z = 0.65$, $p = .52$). The magnitude of radical-RB effect was not significantly different between the same- and different-function conditions (14.6% vs. 21.9%, $t(47) = 1.53$, $p = .13$).

In summary, radical-RB effects were significant and similar in magnitude in the same and different phonetic function conditions. It seems plausible that phonetic radicals either providing a same phonological cue (between friends) or not (between enemies) access the same representation.

It should be noted that the participants' performance was *worse* (i.e. a lower accuracy) when C1 and C2 had the same pronunciation (in the same-function condition) than when they did not (in the different-function condition). That is, an additional inhibitory effect was observed between homophones as compared to non-homophones (i.e. the phonological-RB effect, Bavelier & Potter, 1992; Bavelier et al., 1994). The observation of phonological-RB effect indicates that the sound of C1 and C2 had indeed been accessed during the processing of RSVP stream. Nevertheless, the orthographic effect at the radical level (i.e. radical-RB effect) and phonological effect at the character level (i.e. phonological-RB effect) were additive in modulating participants' performance.

### Discussion of Experiment 2

In Experiment 2, we examined representations of radical function in terms of whether the repeated radicals fulfil their functions. Semantic radicals were examined in Experiments 2A, and phonetic radicals in Experiment 2B. Two main results were observed: first, radical-RB effect was robust and the magnitude was similar when the repeated radicals both fulfilled the function as well as when only one of them did (i.e. in the different-function condition). This result is true for both semantic and phonetic radicals. Second, when C1 and C2 were semantically related, a facilitatory semantic priming effect was observed. But when C1 and C2 were homophones, an inhibitory phonological-RB effect was observed. These opposite effects for semantically related and homophone characters were observed in the same experimental paradigm (i.e. the RB paradigm).

The results therefore suggest that, at the processing level at which radical-RB occurred, the semantic radical either in transparent or opaque characters had the same representation, and similarly the phonetic radicals either in characters with same or different pronunciations have the same representation. This result can be accounted for by the analytic view of Chinese character that radicals are represented before accessing character representations in the orthographic processing (e.g. Chen & Yeh, 2015; Taft, 2006). That a semantic radical or a phonetic radical fulfils its function (i.e. provides semantic or phonetic cue to the character) may be determined by the feedback from the meaning and sound of character-level representations (see the discussion of "the fate of radical representation" in the General discussion).

Considering the results in Experiments 2A and 2B, an alternative way to interpret radical function might be considered. Radicals may simply serve as orthographic inputs that carry orthographic identity and position information (Experiment 1A). Radical function may be represented within the connection network at the character level. Characters having certain levels of semantic-relatedness are linked by facilitatory connections (Experiment 2A), and most of these characters happen to share the same semantic radical (given the fact that the semantic radicals are used to categorise characters). On the other hand, homophones, or phonologically similar characters, are linked by inhibitory connections, and some of these characters happen to share the same phonetic radical. The different connections between characters that share the same semantic radicals vs. those that share phonetic radicals may lead to a spurious idea that semantic and phonetic radicals are represented differently. In addition, given the fact that the semantic and phonological relatedness between two characters lead to different directions of priming (i.e. facilitatory and inhibitory, respectively), one should be very cautious to control the semantic and phonological relatedness between characters in future studies on Chinese character processing.

## General discussion

In the present study, by utilising the RB paradigm, we examined whether a radical is represented by its orthographic identity as well as its position and/or function during Chinese character recognition. In Experiment 1A, the radical-RB effect was larger when the positions of repeated radicals were the same as compared to when they were different, suggesting that radical position was encoded. In Experiment 1B, radical-RB effect was not significantly different when the functions of repeated radicals were the same or different. Comparing the results of Experiments 1A and 1B demonstrates that the reduction of radical-RB effect was larger when changing position than changing function, suggesting that position was more clearly represented than function.

We further examined a fine-grained role of a radical function by manipulating whether the function was fulfilled by semantic radicals and phonetic radicals in Experiments 2A and 2B, respectively. The results demonstrated that radical-RB effect was similar when elicited by semantic radicals either in transparent or opaque characters, and also similar when elicited by phonetic radicals in phonological friends or enemies. These results therefore suggest that radical function was not represented at the radical level. A facilitatory effect was observed between semantically related characters whereas interference was observed between homophones. We suggest that radical function is likely to be embedded in the different networks connecting semantically related characters and between homophones that share the same radical.

In previous research, Yeh and colleagues (Chen & Yeh, 2015; Yeh & Li, 2004) have demonstrated that radical-RB effect genuinely probes the stage of radical processing rather than a sort of character-level inhibition, given that its time course is earlier than character processing and not susceptible to orthographical similarity at the character level. These results therefore suggest that radicals are independently represented (see also Taft, 2006). The current study further demonstrated that a radical representation is encoded with its position information within a character; whereas its functional role, such as whether it serves as a semantic or phonetic radical, or whether it provides a valid or invalid semantic (or phonetic) cue, seems not represented at the radical level.

### *How radical position is represented*

We demonstrate that a radical is represented with its position in Experiment 1A using horizontal characters in which radicals are arranged on the left and right. This is consistent with the results that the sublexical representation of letter clusters or morphemes in English are position-sensitive (Crepaldi et al., 2010; Harris, 2001; McCormick et al., 2009)

Radical position and character structure are highly related, given that the possible positions that radicals can occupy are constrained by each structure type (i.e. radials would be only on left or right in a horizontal-structure character). Hence, researchers chose either structure or position to represent spatial arrangement of radicals in their models/studies (e.g. Perfetti et al., 2005; Taft, 2006; Taft & Zhu, 1997; Yeh, 2000; Yeh & Li, 2002).

In Taft's interactive-activation model consisting stroke, radical, character, and word levels (Taft, 2006; Taft et al., 2000), radical identities are activated by strokes, then attached with a position tag, and finally bounded to a character representation. Here we raise two critical issues that may need to be considered. In this model, position tag is first represented at the stroke level at which strokes are free-floating features. However, when it has not determined how many radicals are going to be constructed by these strokes, there is no clue regarding whether left and right (such as 楓) or top and bottom (such as 嵐) position tags would be formed. This model therefore needs to provide a possible mechanism regarding how position tags can be determined at the stroke level. Second, Taft and colleagues only considered horizontal (i.e. left–right) and vertical (i.e. top–bottom) characters, while the other three types of structures – L-shaped (e.g. 近), P-shaped (e.g. 床), and enclosed (e.g. 困) – were not considered (Yeh & Li, 2002).

In Perfetti et al.'s (2005) computational model, radicals and their spatial relationships are considered as orthographical inputs. There were four kinds of spatial relationships in their model: left–right (such as 楓), top–bottom (such as 嵐), close outside–inside (such as 国), open outside–inside (such as 同). Two issues regarding their model need to be considered. First, these spatial relationships are represented at the same level as radical representations; that is, spatial relationships are merely empty slots and represented independently of radicals. The question remains: how could readers acquire the spatial relationship of a character without knowing its constituent radicals? Second, Perfetti et al. separated *close outside–inside* and *open outside–inside* as two kinds of spatial relationships. The example they used, 国 and 同, are actually categorised as in the same group by native Chinese readers in sorting tasks (Yeh et al., 1997, 1999). On the other hand, L-shaped and P-shaped structures are not included in Perfetti et al.'s model. Perfetti et al.'s spatial constraints of radicals in their computational model therefore do not seem fully supported by empirical evidence collected from Chinese readers.

Previous studies suggest that orthographic information of radicals is essential to form the perception of character structure. For example, among the five structures, horizontal and vertical structures can be identified by skilled readers but not always by non-readers or unskilled readers (Yeh et al., 2003; Yeh, Lin, & Li, 2004). This result suggests that readers' knowledge regarding radicals likely serves as the basis of determining horizontal or vertical structure of a character. The remaining three structures, L-shaped (e.g. 近), P-shaped (e.g. 床), and enclosed (e.g. 困), can be recognised by skilled readers as well as non-readers. This should be attributed to the salient strokes of the critical radical that provide the structure (such as 辶, 广, 囗, respectively, which are called "structural components"). In any case, these results suggest that character structures are identified after the orthography of radicals have been processed to a certain level (though still before the character is identified). Therefore, character structures, and further, the specific positions of radicals, seem to be represented later than the processing of radical identity, rather than earlier or the same as the radical level as suggested by currently available models (Perfetti et al., 2005; Taft, 2006).

In the current study, we only examined the factor of radical position (left or right) in the horizontal-structured characters. We predict that, in vertical-structured characters, radical-RB effect should be reduced when the repeated radical was in the different positions (such as 木 in李-果) than in the same position (such as 木 in李-杏) as well. In future studies, the RB paradigm can be used to examine the interactions between position and structure. For example, whether the same radicals in different structures are encoded differently, such as 壬 in 任 (horizontal), 廷(L-shaped), 呈 (vertical), and 閏 (enclosed); and whether the position code is correlated to the similarity between structures, such as that horizontal and L-shaped characters are more similar than horizontal and vertical characters (Yeh, 2000), can be tested using the RB paradigm.

## How is radical function represented?

We have demonstrated here that the distinct functions of semantic and phonetic radicals, and whether semantic radicals and phonetic radicals fulfil their function (i.e. provide semantic or phonetic cue to the character), seem not to be encoded at the radical level. Radicals therefore are unlikely to carry the functional information at the stage of early orthographic processing. Instead, we suggest that radical function may be represented in the connections between character representations that share the same semantic or phonetic radicals.

That the transparency of semantic radicals is represented at the character level can be linked to English morpheme studies given that semantic radicals in Chinese characters are perhaps comparable to morphemes in English (e.g. Chen & Yeh, 2015; though see Taft, Liu, & Zhu, 1999). A previous neuroimaging study of English words (Devlin, Jamison, Matthews, & Gonnerman, 2004) suggests that words sharing the same morpheme (such as *hunter-hunt*) activate brain areas similar to the addition of orthographically similar words sharing letter clusters (such as *passive-pass*) and semantically related words (such as *sofa-couch*). Davis (2004) therefore proposed a possibility that a morpheme may be represented not in a specific system but distributed in the orthographic and semantic systems of words. A semantic radical, similarly, may be simply represented with its identity and position at the radical level, whereas its function may be represented by the connections between semantically related characters that contain the same sematic radical.

That the function of phonetic radicals is represented at the character level has been proposed by Tzeng, Lin, Hung, and Lee (1995): they adopted the notion of "neighbourhood" in English words and suggest that the cuing function of a phonetic radical is based on the proportion of neighbours that have the same sounds (i.e. friends) vs. different sounds (i.e. enemies). Later studies further demonstrated that the cuing function is not only determined by the proportion of friend and enemy neighbours, but also weighted by the frequency of each neighbourhood character (i.e. a character-level factor, Lee et al., 2004). The phonological cuing function of a phonetic radical is therefore suggested to be established at character level in the neighbourhood (see also Yang, McCandliss, Shu, & Zevin, 2009).

With respect to the current influential models of Chinese character recognition, neither Taft's interactive-activation model nor Perfetti et al.'s computational model includes the representation of radical function at any level. In both models, the meaning of characters is represented in a semantic system, and the sound of characters is represented in a phonological system. We suggest that, in these two systems, lateral connections should be added between character representations in the following ways: facilitatory connections linking semantically related characters in the semantic system, and inhibitory connections linking homophones in the phonological system. Future studies may need to address whether orthographic similarity, such as characters sharing a common radical, increase the weighting between these lateral connections at the character level (e.g. Zhou & Marslen-Wilson, 1999).

## The fate of radical representation

Our results in the current study suggest that radicals are represented by orthographic identity as well as position information, and radicals serve as orthographic inputs to the representations at the character level. Nevertheless, certain studies suggest that a radical further activates its associated meaning and sound automatically irrespective of its possible functional role. As a result, the semantic and phonological information of radicals would likely interact with character meaning and sound. For example, Feldman and Siok (1999a, 1999b) in priming studies demonstrate that an opaque semantic radical (such as 犭 "dog" in 猜 "guess") is inhibited at a later stage of character processing. Stronger evidence has been reported by Zhou and Marslen-Wilson (1999) that the meaning of phonetic radicals (such as 青 "green" in 猜 "guess") is activated and then inhibited during processing the character 猜, given that the meaning of the phonetic radical and the character containing that radical are incongruent. These results suggest that a radical has no functional role since both semantic and phonetic radicals activate associated meanings; however, the activated semantic information of radicals may interfere with character processing, and hence needs to be inhibited after character meaning is accessed.

Taft et al. (2000) suggest that a radical, when it is a simple character (such as 木), is represented as a position-free radical first, and then it can either become a position-sensitive radical representation by combining a position tag, or link to a lemma as a simple character representation. This notion suggests dual roles of radical representation that can be a simple character: a position-free radical or a simple character associated with lemma (see also Taft, 2006). Other semantic radicals that are associated with a particular concept but themselves cannot be simple characters (such as 犭 "dog" and 忄 "heart") should link to a corresponding lemma as well (though see Taft, 2006) in order for them to induce transparency effect reported by Feldman and Siok (1999a, 1999b).

Similarly, early studies of phonetic radicals have also shown that the sounds of phonetic radicals are activated. This phonological information can either facilitate or interfere with the naming process of the whole character when they have the same or different sounds (Flores d'Arcais, Saito, & Kawakami, 1995; Hue, 1992; Liu, Wu, & Chou, 1996; Seidenberg, 1985), which is known as having a regularity effect.[6] Note that these semantic and phonological interactions between radical and character should be taken as feedback-modulation from the character level to the radical level, or as an interaction at the character level when the radical accesses its corresponding lemma representation (see Taft, 2006). Either way, this should not be an effect from the radical level to the character level during feed-forward processing.

Until now, semantic and phonetic radicals do not appear to provide semantic and phonetic information to characters at a sub-character level; however, our results demonstrate that the semantic priming and phonological inhibitory effects between characters were similar irrespective of whether the constituent radical is completely represented or not (i.e. suffers from radical-RB in the latter case). This result seems to violate the traditional view that the meaning and sound of a character would be accessed *after* the orthographic processing of that character was finished, which is based on the radical-level representations as orthographic inputs (Perfetti & Tan, 1998; Taft, 2006; Zhou, Shu, Bi, & Shi, 1999). Nevertheless, some novel evidence suggests that the meaning of a character can be accessed without clear or complete orthographic information. For example, Yeh, He, and Cavanagh (2012) demonstrate that a character can elicit semantic priming effect even when that character is unrecognisable due to visual crowding. Similarly, the sound of a character can be accessed when it is presented at a parafoveal region where detailed orthographic information is lacking (e.g. Tsai et al., 2004). These results therefore challenge current models regarding the orthography, phonology, and semantic processing of Chinese characters.

## Conclusion

According to previous and current studies of radicals in Chinese characters that use the RB paradigm, we summarise radical representation as follows: (1) radical representation is necessary between the stroke and character levels in orthographic processing; (2) radical representations are encoded with orthographic identity and position; (3) radicals are unlikely to be represented by their function; instead, the so-called radical function should be represented by the lateral connections at the character level.

## Notes

1. The other four dictionaries are the Mandarin Daily News Dictionary (He, 1981), the Chinese Character Dictionary (Huang, 1995), the Da-Xue Dictionary (Zhang, 1973), and the Chinese Dictionary (Zhou, 1996).
2. In R, the model was glmer (Accuracy ~ 1 + Position * Function * Radical Repetition + (1 + Position * Function * Radical Repetition|Subject) + (1 + Position * Function * Radical Repetition|Trial), family = binomial, glmerControl (optimizer="bobyqa", optCtrl = list(maxfun = 100000))).
3. The model was glmer (Accuracy ~ 1 + Function * Position * Radical Repetition + (1 + Function * Position * Radical Repetition|Subject) + (1 + Function * Position * Radical Repetition|Trial), family = binomial, glmerControl (optimizer="bobyqa", optCtrl = list (maxfun = 100000))).
4. The model was glmer (Accuracy ~ 1 + Semantic Function * Radical Repetition + (1 + Semantic Function * Radical Repetition|Subject) + (1 + Semantic Function * Radical Repetition|Trial), family = binomial, glmerControl(optimizer="bobyqa", optCtrl = list(maxfun = 100000))).
5. The model was glmer(Accuracy ~ 1 + Phonetic Function * Radical Repetition + (1 + Phonetic Function * Radical Repetition |Subject) + (1 + Phonetic Function * Radical Repetition |Trial), family = binomial, glmerControl(optimizer="bobyqa", optCtrl = list(maxfun = 100000))).
6. To date, nevertheless, there seems to be a lack of evidence that suggests that semantic radicals have the activation of their associated sounds.

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**Appendix 1:** Stimulus materials used in Experiment 1A (1 and 2) and 1B (1 and 3)

| (1) | Same position and same function | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Same semantic radical | | | | Same phonetic radical | | |
| | UR | Left | Left | Repeated radical | UR | Right | Right | Repeated radical |
| | 剛 | 院 | 除 | 阝 | 怪 | 始 | 治 | 台 |
| | 胖 | 洞 | 洗 | 氵 | 耶 | 格 | 略 | 各 |
| | 乾 | 偶 | 偏 | 亻 | 值 | 根 | 眼 | 艮 |
| | 暗 | 詳 | 誠 | 言 | 哈 | 計 | 針 | 十 |
| | 組 | 強 | 張 | 弓 | 詩 | 瑞 | 端 | 耑 |
| | 啡 | 凌 | 准 | 冫 | 倚 | 探 | 深 | 罙 |
| | 媒 | 殘 | 殖 | 歹 | 瞭 | 賺 | 謙 | 兼 |
| | 狠 | 缸 | 缺 | 缶 | 即 | 決 | 快 | 夬 |
| | 浩 | 航 | 船 | 舟 | 眠 | 俗 | 浴 | 谷 |
| | 託 | 徐 | 徒 | 彳 | 績 | 購 | 講 | 冓 |
| | 桃 | 孤 | 孫 | 子 | 妹 | 狗 | 拘 | 句 |
| | 評 | 細 | 終 | 糸 | 弱 | 悔 | 梅 | 每 |
| | 解 | 場 | 塊 | 土 | 割 | 愉 | 偷 | 俞 |
| | 洪 | 映 | 昨 | 日 | 朋 | 阿 | 河 | 可 |
| Mean character frequency | 214 | 213 | 198 | | 266 | 279 | 241 | |
| Mean stroke count | 11 | 10 | 11 | | 11 | 11 | 11 | |

| (2) | Different position (same function) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Same semantic radical | | | | Same phonetic radical | | |
| | UR | Left | Right | Repeated radical | UR | Left | Right | Repeated radical |
| | 緝 | 螃 | 融 | 虫 | 誰 | 數 | 樓 | 婁 |
| | 晚 | 夠 | 夥 | 多 | 冷 | 攻 | 江 | 工 |
| | 打 | 加 | 功 | 力 | 物 | 改 | 記 | 己 |
| | 派 | 呼 | 和 | 口 | 慢 | 預 | 野 | 予 |
| | 阪 | 妒 | 妝 | 女 | 陣 | 封 | 佳 | 圭 |
| | 制 | 服 | 朗 | 月 | 松 | 刻 | 孩 | 亥 |
| | 磕 | 駝 | 鴨 | 鳥 | 賴 | 歐 | 樞 | 區 |
| | 颱 | 魁 | 魂 | 鬼 | 印 | 收 | 叫 | 丩 |
| | 矮 | 馳 | 馮 | 馬 | 技 | 助 | 姐 | 且 |
| | 拜 | 配 | 酒 | 酉 | 硬 | 斯 | 棋 | 其 |
| | 僧 | 辣 | 辟 | 辛 | 孰 | 剖 | 培 | 咅 |
| | 敲 | 羯 | 群 | 羊 | 懊 | 豁 | 轄 | 害 |
| | 諾 | 積 | 穌 | 禾 | 縣 | 敵 | 摘 | 啇 |
| | 垮 | 帖 | 帥 | 巾 | 僕 | 甄 | 煙 | 垔 |
| Mean character frequency | 195 | 187 | 240 | | 246 | 273 | 240 | |
| Mean stroke count | 11 | 12 | 12 | | 11 | 11 | 11 | |

| (3) | Different function (same position) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Same left radical | | | | Same right radical | | |
| | UR | Semantic radical | Phonetic radical | Repeated radical | UR | Semantic radical | Phonetic radical | Repeated radical |
| | 掉 | 粗 | 料 | 米 | 行 | 北 | 此 | 匕 |
| | 住 | 秋 | 利 | 禾 | 帳 | 靖 | 猜 | 青 |
| | 純 | 躲 | 射 | 身 | 瑄 | 凱 | 飢 | 几 |
| | 珠 | 耿 | 恥 | 耳 | 狼 | 尉 | 耐 | 寸 |
| | 初 | 財 | 敗 | 貝 | 肥 | 故 | 玫 | 攵 |
| | 貌 | 嘘 | 鳴 | 口 | 邦 | 段 | 役 | 殳 |
| | 煉 | 皓 | 魄 | 白 | 廷 | 助 | 幼 | 力 |
| | 餅 | 鈞 | 欽 | 金 | 歧 | 卦 | 赴 | 卜 |
| | 硫 | 脖 | 豚 | 月 | 晚 | 雄 | 推 | 隹 |
| | 指 | 於 | 放 | 方 | 執 | 欲 | 軟 | 欠 |
| | 淺 | 靶 | 勒 | 革 | 源 | 項 | 煩 | 頁 |
| | 務 | 祥 | 視 | 示 | 跋 | 甜 | 鉗 | 甘 |
| | 城 | 校 | 相 | 木 | 弧 | 狀 | 吠 | 犬 |
| | 崎 | 軸 | 斬 | 車 | 叔 | 形 | 杉 | 彡 |
| Mean character frequency | 301 | 259 | 305 | | 219 | 241 | 225 | |
| Mean stroke count | 11 | 11 | 11 | | 10 | 10 | 9 | |

UR: unrepeated
The symbols used in this study: & ⁎ ∮ ◎ § @ ♂ $ Φ Ω ≠ ≧ ≒ ∞ ⊄ % VII Σ ︸ ︷ ☆ ◇ ▽ △ ⊿ ★ ▲ ◆ ◤ ◢ ◣ ◥ ●

**Appendix 2:** Stimulus materials used in Experiment 2A

| | C1 | | | | C2 | Repeated Semantic Radical |
|---|---|---|---|---|---|---|
| | Same function | | Different function | | | |
| | UR | R | UR | R | | |
| | 服 | 袖 | 段 | 裕 | 袍 | 衤 |
| | 耕 | 稻 | 徒 | 秘 | 秧 | 禾 |
| | 號 | 唸 | 陳 | 唯 | 喊 | 口 |
| | 明 | 皓 | 使 | 的 | 皎 | 白 |
| | 硬 | 錫 | 規 | 錄 | 鋼 | 金 |
| | 油 | 脂 | 按 | 脆 | 胖 | 月 |
| | 條 | 根 | 晚 | 格 | 枝 | 木 |
| | 滾 | 軸 | 銷 | 軟 | 輪 | 車 |
| | 碎 | 粒 | 旗 | 粗 | 粉 | 米 |
| | 停 | 河 | 陽 | 法 | 泊 | 氵 |
| | 羚 | 狼 | 砥 | 猜 | 狸 | 犭 |
| | 叔 | 姊 | 旺 | 妨 | 姑 | 女 |
| | 帆 | 船 | 垮 | 般 | 航 | 舟 |
| | 述 | 語 | 射 | 諸 | 話 | 言 |
| | 濃 | 醉 | 瑰 | 酷 | 醇 | 酉 |
| | 脹 | 飼 | 煥 | 飾 | 飽 | 食 |
| | 獸 | 貓 | 糟 | 貌 | 豹 | 豸 |
| | 牆 | 碑 | 賜 | 確 | 磚 | 石 |
| | 錦 | 綿 | 瞧 | 給 | 綢 | 糸 |
| | 跨 | 騁 | 粹 | 駭 | 騎 | 馬 |
| Mean character frequency | 105 | 2224 | 223 | 210 | 123 | |
| Mean stroke count | 12 | 12 | 12 | 12 | 12 | |

UR: Unrepeated R: Repeated

**Appendix 3:** Stimulus materials used in Experiment 2B

| | C1 | | | | | |
|---|---|---|---|---|---|---|
| | Same function | | Different function | | | |
| | UR | R | UR | R | C2 | Repeated phonetic radical |
| | 憒 | 紛 | 斜 | 扮 | 粉 | 分 |
| | 即 | 汲 | 邦 | 圾 | 級 | 及 |
| | 拔 | 把 | 壯 | 肥 | 靶 | 巴 |
| | 蜈 | 悟 | 鴉 | 語 | 唔 | 吾 |
| | 佯 | 殃 | 卵 | 映 | 泱 | 央 |
| | 勸 | 銓 | 賄 | 栓 | 詮 | 全 |
| | 紙 | 脂 | 郭 | 詣 | 指 | 旨 |
| | 粒 | 狸 | 旅 | 埋 | 哩 | 里 |
| | 肆 | 伺 | 欺 | 祠 | 飼 | 司 |
| | 洞 | 凍 | 副 | 陳 | 棟 | 東 |
| | 輕 | 情 | 救 | 猜 | 清 | 青 |
| | 嘛 | 瑪 | 頃 | 馮 | 螞 | 馬 |
| | 項 | 橡 | 群 | 豫 | 像 | 象 |
| | 助 | 注 | 佛 | 往 | 柱 | 主 |
| | 夠 | 購 | 德 | 講 | 構 | 冓 |
| | 娛 | 愉 | 飾 | 偷 | 瑜 | 俞 |
| | 垢 | 夠 | 拜 | 拘 | 狗 | 句 |
| | 馱 | 駝 | 枝 | 蛇 | 陀 | 它 |
| | 哎 | 挨 | 殷 | 俟 | 埃 | 矣 |
| | 眠 | 綿 | 禍 | 錦 | 棉 | 帛 |
| | 褥 | 孺 | 頗 | 懦 | 儒 | 需 |
| | 獨 | 讀 | 證 | 續 | 瀆 | 賣 |
| | 杉 | 珊 | 郊 | 柵 | 姍 | 冊 |
| | 愧 | 潰 | 竭 | 遺 | 饋 | 貴 |
| Mean character frequency | 131 | 191 | 102 | 129 | 218 | |
| Mean stroke count | 11 | 12 | 11 | 12 | 12 | |

UR: unrepeated R: repeated.