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Binding radicals in Chinese character recognition: Evidence from repetition blindness

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ABSTRACT

Many Chinese characters consist of two radicals and it has long been debated whether characters are decomposed into radicals during the processing of character recognition. Here we examine this issue utilizing a novel repetition blindness (RB) paradigm that provides a sensitive measure of internal representations in the early stages of processing. We found a radical-RB effect (i.e., two characters are less likely to be correctly reported when they share a common radical) for both high- and low-frequency characters (Experiment 1). Experiment 2 was to exclude the possibility that radical-RB effect can be explained by character-level similarity. Finally, the radical-RB effect was found to be robust irrespective of how frequently a radical is presented in different characters (Experiment 3). All these results suggest that radicals are represented during the processing of characters, supporting the analytic (rather than holistic) hypothesis of Chinese character recognition. A model that highlights a dynamic process of binding radicals to construct character representations is proposed.

Introduction

How words are recognized is a critical issue in understanding the process of reading English (see Rastle & Davis, 2008, for a review). Take a word comprised of multiple morphemes (such as *teacher* consisting of *teach* and *er*) for example. These words are likely decomposed into morphemes at an early stage and serve as mediators to access the mental lexicon (e.g., Longtin & Meunier, 2005; Rastle, Davis, & New, 2004; Taft, 1994, 2003). On the other hand, a word may be recognized holistically and its decomposition into morphemes only occurs after lexical access (Marslen-Wilson, Tyler, Waksler, & Older, 1994; Plaut & Gonnerman, 2000; Rueckl & Raveh, 1999). The issues about Chinese character recognition have been undergoing a very similar debate although Chinese script is a completely different writing system from English. The primary goal of the present study is to investigate whether Chinese characters are necessarily decomposed into sub-character units in the orthographic processing.

Holistic vs. analytic hypothesis of Chinese character processing

About 70–80% of traditional Chinese characters are *phonograms* (形聲字 [síng sheng zìh]), consisting of two radicals. Take the phonogram 楓 ([fong], “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 ([mù], “tree”) conveys the semantic category, and the radical 風 ([fong], “wind”) provides a phonological cue of the whole character. Accordingly, 木 is semantic radical (部首 [bù shǒu]) and 風 is the phonetic radical (聲旁 [sheng páng]) of the

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character 楓 (see Liu, Su, & Chen, 2001; Zhou, Ye, Cheung, & Chen, 2009). In general, 75% of the phonograms consist of a semantic radical on the left and a phonetic radical on the right (Perfetti & Tan, 1999). That the meaning and the sound of a character are conveyed by different radicals in a phonogram is a unique property of Chinese characters, though the mappings between radicals and a character are not always as close as in the above example.

In a Chinese text, each character occupies a constant size irrespective of the visual complexity (i.e., the number of constituent strokes). In addition, each character usually corresponds to one syllable and one morpheme (e.g., Taft, 2006). These properties suggest a *holistic hypothesis* that each character itself is an orthographic processing unit (e.g., Chen & Liu, 2000). Radicals are then processed *after* the recognition of characters if the task requires the decomposition of characters into radicals; for example, when the participants were instructed to detect the occurrence of a particular radical embedded in characters (e.g., Chen, 1984; Cheng, 1981; Tao & Healy, 2002; Yu, Cao, Feng, & Li, 1990).[1]

Later studies propose an *analytic hypothesis* that radicals are processed first and then combined in order to access a character representation. This hypothesis is supported by studies demonstrating that character recognition is influenced by certain properties of radicals. These properties include position (or structure) of radicals (i.e., how radicals are arranged in a character, see Taft & Zhu, 1997; Taft, Zhu, & Peng, 1999 ; Yeh & Li, 2002; Yeh, Li, & Chen, 1997) and the function of radicals (i.e., whether a semantic or phonetic radical provides information to a character, see Fang, Horng, & Tzeng, 1986; Feldman & Siok, 1999a; Flores d'Arcais, Saito, & Kawakami, 1995; Leck, Weekes, & Chen, 1995; Liu, Chen, & Sue, 2003; Seidenberg, 1985).

Evidence for analytic, holistic, or hybrid hypothesis from the character decision task

Character decision task (CDT, Taft, 2006) is the most frequently used paradigm that examines the orthographic processing of Chinese characters.[2] In this task, participants are instructed to discriminate whether the target is a character or non-character as soon and as accurately as possible. Participants' correct reaction times (RTs) in character trials are analyzed. A typical result of CDT demonstrates that participants' mean RT is faster for recognizing high-frequency (HF) characters than low-frequency (LF) characters (Liu, Wu, & Chou, 1996; Zhu & Taft, 1994).

The results utilizing CDT to examine the character decomposition process are, nevertheless, inconsistent. For example, *radical combinability* (the number of characters containing a given radical, see Feldman & Siok, 1997; or called *radical frequency* in Taft & Zhu, 1997) has been shown to influence CDT results. That is, participants' RT was shorter when the target character consisted of a high-combinability radical rather than a low-combinability one. However, such radical effects in CDT are often observed only in LF characters, but not necessarily in HF characters (e.g., Ding, Peng, & Taft, 2004; Li & Chen, 1999; Zhu & Taft, 1994). Evidence from CDT cannot be used to verify either the analytic or holistic hypothesis because each is supported by studies using only a subgroup of characters. One explanation is that LF characters are processed analytically, whereas HF characters are processed holistically due to familiarity (i.e., the unitization hypothesis, Healy, 1994; Tao & Healy, 2002). This third hypothesis suggests that the mechanism of Chinese character recognition is a *hybrid* of analytic and holistic processing.

An alternative explanation regarding the radical effects observed only in LF but not in HF characters is proposed by Ding et al. (2004, p. 532): HF characters reach their recognition threshold rapidly, and thus participants' RT to judge them is too short to reveal any facilitatory effect elicited by high-combinability radicals. This explanation, therefore, suggests a limitation that the CDT method is perhaps not sensitive enough to probe radical representations in HF character processing.

Another series of studies has examined the orthographic priming effect between two characters by presenting the target of CDT following a prime character that shares a radical (known as *primed-CDT*). Once again, contrary results have been reported, especially between those studies in which prime and target are presented at very similar stimulus onset asynchronies (SOAs). For example, Ding et al. (2004) and Feldman and Siok (1999a) reported a *facilitatory* effect when prime and target had a common radical (i.e., the RTs were shorter as compared to when they had no common radical) when the SOA was 43 ms. This facilitatory effect was only observed when the *target* was a LF character rather than a HF character, thus suggesting that the positive priming effect was elicited by the shared radical representation (Ding et al., 2004). On the other hand, Wu and colleagues (Wu & Chen, 2000, 2003; Wu & Chou, 2000) reported an *inhibitory* effect when prime and target shared a common radical (i.e., the RTs were longer as compared to when they had no common radical) when the SOA was 50 ms. Wu and Chen (2003) further demonstrated that the inhibition was only elicited by a *HF prime* rather than a LF or a pseudo-character prime. Wu and Chen suggested that this orthographic inhibitory effect is attributed to the fact that the quickly-activated character representation (i.e., the HF prime) inhibits representations of other orthographically-similar characters (including the target) during lexical access (i.e., a character-level inhibition), while radicals embedded in a character were not represented. These discrepant results, as well as the different mechanisms proposed regarding the priming at the radical or character level, are likely determined by the level at which the *prime* character was processed

[1] Utilizing a radical detection task that relies on participants' explicit report of the target radical may probe a conscious hierarchical processing which constitutes a reversed order of the unconscious hierarchical processing (e.g., Hochstein & Ahissar, 2002). That is, it is likely that radicals are processed before characters in the unconscious processing, whereas characters reach conscious level before radicals in the conscious processing (see Chen & Yeh, 2009). Therefore, discrepant results observed using explicit tasks (such as radical detection task) vs. implicit tasks (such as the character detection task) regarding radicals are very likely due to different mechanisms being probed.

[2] Naming task is another commonly-used paradigm to study Chinese character recognition. Nevertheless, naming task is often used to examine the function of phonetic radicals, and this is beyond the scope of the present study.

(i.e., whether the character representation of the prime has been accessed, see Humphreys, Evett, Quinlan, & Besner, 1987). The processing level of prime characters in these studies was, unfortunately, unclear when using the primed-CDT paradigm since participants were not required to respond to the prime character.

In summary, even though CDT studies have provided much understanding about the radical processes of Chinese characters, inconsistent results have been reported. These inconsistencies may be due to the limitations of CDT (or primed-CDT) and utilizing new study methods is necessary. The experimental paradigm that measures participants' identification accuracy of characters presented with limited time is suggested to be a more appropriate dependent variable than the RT measure used in CDT when examining internal representations at the early processing stage (see Norman & Bobrow, 1975; Prinzmetal, McCool, & Park, 2005; Santee & Egeth, 1982). In addition, the identification of both target character and prime character need to be measured in order to ensure the processing level of different kinds of prime. We consider a repetition blindness (RB) paradigm as an optimal alternative to probe the radical processing of Chinese characters.

Radical-RB effect in Chinese characters

RB refers to a failure to detect or report the second occurrence of a repeated item in a rapid serial visual presentation (RSVP) stream (Kanwisher, 1987). For example, the sentence "I prefer green *tea* for *tea* time" presented word by word in RSVP may be sometimes misreported as "I prefer green *tea* for time", even though such an error may lead to an ungrammatical sentence. The RB paradigm has been used to explore the internal representations of alphabetic words. For example, RB occurs not only with identical words, but also for orthographically similar words that share letters (e.g., *c<u>ome</u>* and *h<u>ome</u>*; Bavelier, Prasada, & Segui, 1994; Kanwisher & Potter, 1990). In the case of RB for orthographically similar words, it is suggested that RB occurs at the level of sub-lexical *letter clusters* (i.e., the <u>*ome*</u> in the above example, see Bavelier et al., 1994; Harris & Morris, 2001, 2004; Morris & Harris, 1999). This is consistent with various other influential models that suggest that letter clusters are represented before accessing word representations in alphabetic systems (e.g., Humphreys, Evett, & Quinlan, 1990; Plaut, McClelland, Seidenberg, & Patterson, 1996; Prinzmetal, Hoffman, & Vest, 1991; Seidenberg & McClelland, 1989).

In a similar vein, Yeh and Li (2004) reported an RB effect for identical Chinese characters (i.e., *the character-RB effect*) as well as for two characters that share the same radical (i.e., *the radical-RB effect*). In the latter case, for example, the two critical items in a RSVP stream were 松 and 村 (called C1 and C2 for critical item 1 and 2, which can be compared to the prime and target in the primed-CDT paradigm), both of which contain the semantic radical 木 on the left (see Fig. 1, the radical 木 denoted by A below it). Even though the participants' task was to report all of the characters presented in the RSVP stream, they sometimes omitted the repeated radical of C2, and reported 松 and 寸 in the above example; that is, the repeated radical 木 in C2 was missing, and only the residual radical 寸 was reported (denoted by D). Critically, Yeh and Li demonstrated that the radical-RB effect occurred at a shorter interval between C1 and C2 compared to the character-RB effect, which suggests that radicals are processed earlier than are characters.

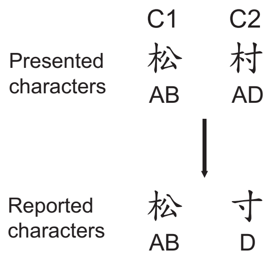

Fig. 1. An example of radical RB in Chinese characters. C1 (松) and C2 (村) share a radical 木 (labels as A). After radical RB occurs, the radical 寸 (labels as D) is the residual radical (see Experiment 3B).

In the present study, we used the RB paradigm to examine the analytic, holistic, or a hybrid hypothesis of Chinese character processing. We aim to demonstrate that the radical-RB effect is genuinely attributed to the fact that one of the repeated radicals was unseen, and that the effect is robust even when several properties pertaining to character or radical are manipulated. In Experiment 1, the character frequency of C1 is manipulated in order to examine whether radicals are represented either embedded in a HF or in a LF character. In Experiment 2, the proportion of the repeated radical relative to the unrepeated radical within a character is manipulated in order to verify that the radical-RB effect is attributed to the fact that the repeated radical was lost while being insensitive to whether the proportion of that radical in a character is small or large. In Experiment 3, the combinability of radicals is manipulated in order to demonstrate that radicals are represented whether they are frequently-used or not (i.e., high or low radical combinability). In all experiments, both semantic and phonetic radicals were tested. In summary, we observed a reliable radical-RB effect in all experiments suggesting that characters were decomposed and radicals were represented. Based on the current results and the already-proposed mechanism of RB, we put forward a dynamic framework of Chinese character processing in the General Discussion.

Experiment 1

In Experiment 1, we examine whether the radical-RB effect can be reliably observed in both HF and LF characters. The character frequency of C1 was manipulated as HF or LF, and C2 was held constant in a medium frequency range. This design aimed to probe whether HF- and LF-C1s were decomposed with comparable C2s. In addition, if radical-RB occurred during the orthographic processing of Chinese characters, it should be modulated by relative frequency of C1 and C2. Such effect has been demonstrated in the letter-cluster RB in English words, and the result suggests that the orthographic representations involved

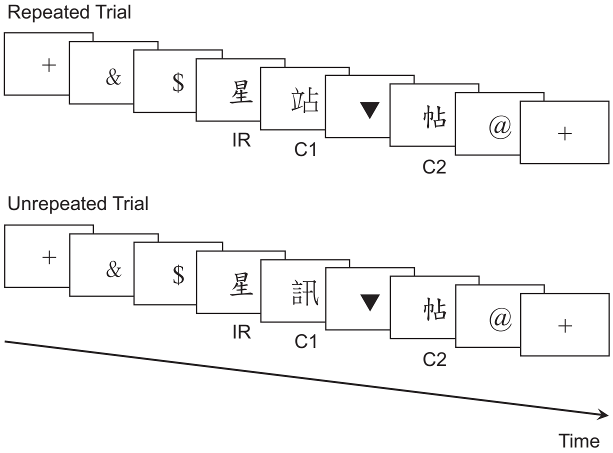

Fig. 2. Examples of the RSVP sequence used in the present study. Three characters and four symbols were presented in each trial. In the repeated trial, one radical (e.g., 占) was repeated in C1 (站) and C2 (帖). In the unrepeated trial, all displays were the same as those in the repeated trial except for C1 (訊) that did not share any radical with C2. The presentation duration of C1 was manipulated (43, 57, or 86 ms in Experiment 1; 43 or 57 ms in Experiment 2, and 43 ms in Experiments 3A and 3B). Other stimuli were presented for 43 ms.

in letter-cluster RB and in early visual word recognition are similar (Bavelier et al., 1994).

In addition, we also aimed to verify that this radical-RB effect revealed a typical pattern over time by manipulating the presentation duration of C1 because presumably, a genuine radical-RB effect should show a decreased magnitude when the SOA between C1 and C2 increases (see Harris & Morris, 2001; Kanwisher, 1987; Yeh & Li, 2004). The typical radical-RB effect in both HF- and LF-C1 conditions would support the analytic hypothesis.

Two alternative predictions might be proposed: according to the hybrid hypothesis in terms of the CDT results that suggest that only LF characters were decomposed while HF characters were not (e.g., Ding et al., 2004; Li & Chen, 1999), the radical-RB effect should be only observed in the LF-C1 condition. According to the holistic hypothesis based on the primed-CDT results, the inhibitory effect between orthographically-similar characters is due to the character-level inhibition (Wu & Chen, 2003) and the radical-RB effect should be observed only in HF characters. Furthermore, this effect should reveal an atypical pattern that the magnitude increases with the increasing SOA between C1 and C2 because the inhibition from character representations of C1 to the orthographically similar C2 is strongest at a few hundreds of milliseconds after the onset of C1 (see Chialant & Caramazza, 1997; though see Harris & Morris, 2001).

Method

Participants

Three groups of 48 undergraduates studying at National Taiwan University (NTU) participated in this experiment for course credit. They are native speakers of Mandarin Chinese and were naïve regarding the purpose of this experiment. All of them had normal or corrected-to-normal vision by self-report. The protocol was approved by the academic and ethical committee in the Department of Psychology, NTU.

Stimuli

Stimuli were presented on a 15-in. color-calibrated monitor and controlled by a personal computer. The refresh rate of the monitor was set at 70 Hz. Participants sat at a viewing distance of 60 cm in a dimly lit chamber.

Each trial consisted of seven items in RSVP, made up of three characters and four symbols that were white and presented one at a time in the center of a black background (Fig. 2). The three characters were C1, C2, and an irrelevant character (IR). All C1 and C2 used in the present study were characters with horizontal structure (such as 站), and had their semantic radical (e.g., 立) on the left and phonetic radical (e.g., 占) on the right. IR was a character with vertical structure (such as 星, the radical 日 is on top of the other radical 生), a distinctly different structure from C1 and C2 to make it perceptually separate from the two critical characters (Yeh & Li, 2002). IR was included in RSVP in order to provide an adequate task difficulty when probing radical-RB effect (see Yeh & Li, 2004). Also, in order to avoid any unwanted priming effect, the three characters did not have obvious semantic relationships, nor did they rhyme.

The IR and C2 were in the Chia font, subtended at a visual angle of 1.15° × 1.24° (width × height). C1 was in the Fong font (1.53° × 1.43°), which was slightly larger than C2. Therefore, the two critical characters were physically distinct in order to avoid the repeated radical in C1 and C2 temporally merging together due to their identical shape. A fixation cross (1.15° × 1.24°) was presented at the beginning and the end of each RSVP sequence. In each trial, four symbols without repetition were selected randomly from a set of 30 symbols, including &, ∇, ≒, $, etc., subtended from 1.21° × 0.80° to 1.43° × 1.24°.

Design

Four factors were manipulated. Three of them, *Radical Repetition* (repeated or unrepeated), *C1 Frequency* (HF-C1 or LF-C1), and *Radical Function* (semantic or phonetic)[3] were within-participant factors. The fourth factor, *C1 Duration* (43 ms, 57 ms, and 86 ms), was manipulated on a between-participant basis in order to avoid the possibility that participants would view the same stimuli three times.

Two groups of 16 characters that have an appearance in daily newspapers in the range of 10–505 per million (according to Tsai, 1996; see Appendix A) were selected to be C2 for each of the semantic-radical and phonetic-radical condition. The character frequency between these two conditions was matched ($p > .05$). Although the stroke count of these two groups of characters differed ($F(1,30) = 5.00$, $p < .05$), this difference did not systematically influence our results.[4] The function of the radicals in each character was defined according to the *Chinese dictionary* published by the Ministry of Education in Taiwan (2000) and the manual for phonetic radicals (Liu et al., 2001).

Each C2 was paired with four kinds of C1 (C1 Frequency × Radical Repetition): HF-C1/repeated, HF-C1/unrepeated, LF-C1/repeated, and LF-C1/unrepeated. The frequency of HF-C1 usage was higher than 313 per million. Although this range overlaps with the range of C2 frequency, there were only two C2s with frequency higher than 313 per million and their paired HF-C1s had even higher frequencies. The frequency of LF-C1 was lower than 6 per million. C1 and C2 had one same radical in the repeated trials but not in the unrepeated trials. The frequency of the HF-C1 in the four conditions (Radical Repetition × Radical Function, in a two-way analysis of variance, ANOVA) did not differ significantly, nor did those of LF-C1 ($ps > .1$). The stroke counts of C1 were matched with those of C2. The stroke counts of C1 in the eight conditions (Radical Repetition × C1 Frequency × Radical Function) were submitted to a three-way ANOVA. Neither any main effect nor any interaction was significant (all $ps > .05$).

The factors of Radical Repetition and C1 Frequency were in a yoked design: four versions were constructed so that, in each version, a given C2 was only presented once and paired with a C1 in one of the four possibilities (C1 Frequency × Radical Repetition). The number of trials for each type of C1 was counter-balanced across versions. Each version consisted of 32 critical trials, 16 repeated and the other 16 unrepeated. In addition, there were 16 filler trials that simulated the perception when radical-RB occurred: the C1 and C2 pair in the filler trial (e.g., 剴 and 食) was designed by removing the repeated radical (e.g., 几) of C2 from a pair of characters that shared a common radical (e.g., 剴 and 飢, which shared the common radical 几 on the right). The purpose of adding these trials was to discourage participants from trying to strategically fill in a radical in C2 when they only perceived one radical (presumably the residual radical). Altogether, there were 48 trials in each version, and each version was conducted with 12 participants (i.e., a quarter of the 48 participants). For each participant, the presentation order of the 48 trials was completely randomized.

The fourth factor (C1 Duration) was designed to investigate the time course of the radical-RB effect. C1 was presented either for 43, 57, or 86 ms, while C2 was controlled to be constant for 43 ms in all three conditions. These presentation durations were chosen based on Yeh and Li (2004) and our pilot results. Each of the three C1-duration conditions was conducted with a group of 48 participants.

Procedure

Participants initiated a trial by pressing the keyboard space bar. At the beginning of each trial, a beep sound was presented for 150 ms, followed by a fixation cross for 500 ms and the RSVP stream. After the RSVP sequence, the fixation cross remained on the screen, waiting for the participant to write down their answers and then to press the space bar to proceed with the next trial. The seven items in the RSVP were in the order of symbol (S), S, IR, C1, S, C2, and S. Each item was presented for 43 ms, except for the varied duration of C1. Participants were asked to write down the three characters (i.e., IR, C1, and C2) in each trial. They were encouraged to guess or write down any part of the character if not certain. No feedback was given to the participants regarding the accuracy of their responses.

A practice session with seven unrepeated trials was conducted before the main experiment. The characters presented in the practice trials were not used in the main experiment. If the participant failed to report at least three trials correctly, the practice session was rerun again. In the second practice session, the participant reported the characters orally, and the experimenter made sure that they had followed the instructions and had seen three characters (not necessarily correct) in each trial. Less than 10% of the participants failed the first run, and all participants were able to meet the requirements and proceed with the main experiment after the second session.

Results

In all the experiments reported in the present study except Experiment 3B (details follow), the accuracy of participants' performance was calculated based on the percentage of trials of which C1 and C2 were both correctly reported, regardless of the order of these reports (Kanwisher, 1987; Park & Kanwisher, 1994). The accuracy data (Fig. 3) were submitted to a mixed-effect model that considers both subjects and items as random variables (SPSS 20, Armonk, NY: IBM Corp, see Brysbaert, 2007) on

[3] Given the characters used in the current study have their semantic radical on the left and phonetic radical on the right, it is hard to tease apart whether the significant radical effect could be attributed to the fact that these two types of radicals have different functions (semantic and phonetic) or positions (left and right). Nevertheless, given that our ultimate goal is to understand the role of radical function during Chinese character processing as the mass of literature does, we use "Radical Function" to label the factor in order to compare our results in the follow-up study (see General Discussion).

[4] The mean character stroke count of C2 was higher in the semantic-radical condition than in the phonetic-radical condition (11.1 vs. 9.4), which means that the C2 in the semantic-radical condition was more complex visually at the character level. However, the results revealed that the accuracies in the semantic-radical and the phonetic-radical conditions were not significantly different.

the fixed factors of Radical Repetition, C1 Frequency, Radical Function and C1 Duration.[5]

The results revealed that two main effects were significant: Radical Repetition and C1 Frequency. The radical-RB effect was significant in that the accuracy was higher in the unrepeated condition than in the repeated condition (56.8% vs. 44.7%, $F(1,33) = 28.04$, $p < .001$). The accuracy was higher also in the HF-C1 than in the LF-C1 condition (61.5% vs. 40.1%, $F(1,33) = 90.87$, $p < .001$).

Two two-way interactions were significant (see Fig. 4). Radical Repetition × C1 Duration was significant ($F(2,4378) = 5.43$, $p < .005$). The RB effect was significant in all three C1 duration conditions (43 ms: 17.8%, $t(47) = 8.16$, $p < .001$; 57 ms: 11.2%, $t(47) = 5.02$, $p < .001$; 86 ms: 7.2%, $t(47) = 3.03$, $p < .005$). The significant interaction was attributed to the fact that the radical-RB effect was larger at the 43 ms than at the 86 ms condition (*post hoc* test with Bonferroni correction, $p < .005$). Radical Repetition × Radical Function was significant ($F(1,33) = 4.98$, $p < .05$). Radical-RB effect was significant for both phonetic radicals (17.0%, $t(143) = 8.94$, $p < .001$) and for semantic radicals (7.1%, $t(143) = 4.09$, $p < .001$), and the magnitude was larger in the phonetic-radical than in the semantic-radical condition. The two way interaction between Radical Repetition × C1 Frequency was marginally significant ($F(1,33) = 3.12$, $p = .09$). Radical-RB effect was significant in both HF-C1 (16.1%, $t(143) = 7.86$, $p < .001$) and LF-C1 condition (8.0%, $t(143) = 4.34$, $p < .001$). This interaction was attributed to the fact that the magnitude of radical-RB was larger in the HF-C1 than LF-C1 condition ($t(143) = 2.89$, $p < .005$). No other higher-level interaction was significant (all $Fs < 1.97$, $ps > .14$).

The participants' errors in the repeated trials were further analyzed. For example, when two critical characters shared the same radical (e.g., 綾-綜, they share the left semantic radical 糸), the participants sometimes either omitted the repeated radical (e.g., reported 綾-宗) or replaced it with another radical (e.g., reported 綾-棕). We define such errors as *explicit radical-RB*. Nevertheless, similar errors may also occur in unrepeated trials (e.g., in the trial with C1–C2 as 鯨-綜, 鯨-宗 was reported). We therefore compared the proportion of such errors out of total trials in the repeated and unrepeated conditions. The results suggest that the proportion of explicit radical-RB was significantly higher in the repeated than unrepeated trials at all three SOAs (see Table 1a). Furthermore, the explicit radical-RB in the repeated trials occurred more often in C2 than in C1 at all three SOAs (see Table 1b).

We also analyzed the accuracy of filler trials in order to see how often the participants filled in a radical in C2 when they perceived only a single radical. The accuracy of C1 (e.g., 凱) and C2 (e.g., 食) in the filler trials was calculated separately. The accuracies of (C1, C2) across three C1

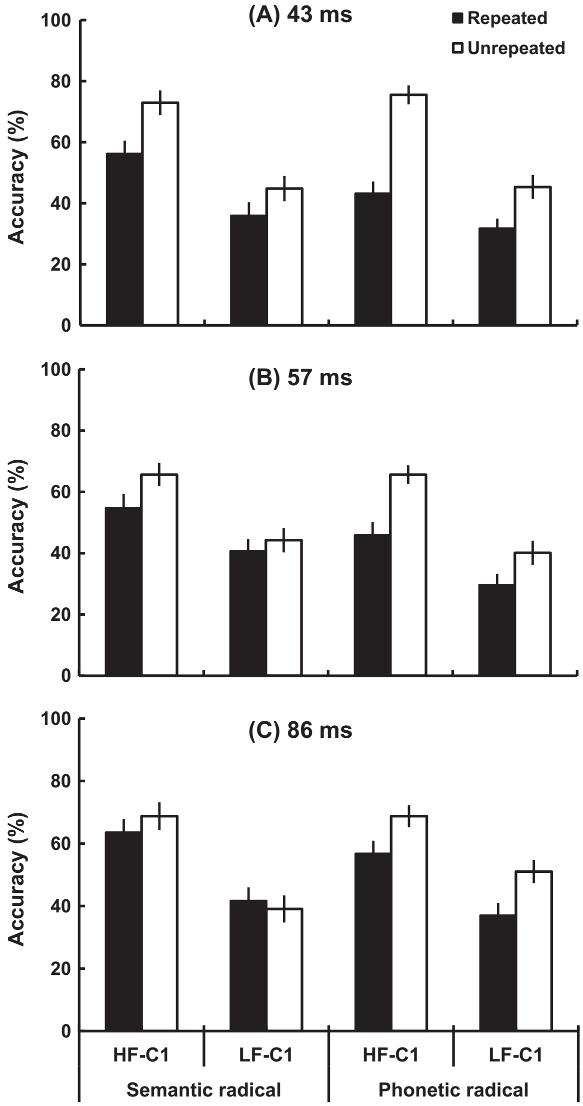

Fig. 3. The mean accuracy of participants' character identification performance (both C1 and C2 were correct) in Experiment 1, where C1 was presented for (A) 43 ms; (B) 57 ms; and (C) 86 ms. The error bars indicate ±1 standard error of the means.

[5] We also analyzed C1 accuracy and C2 accuracy separately in order to confirm whether the manipulations of C1 frequency and C1 Duration effectively modulate participants' identification accuracy of C1, and whether the radical-RB effect mainly occurred in C2 (Kanwisher, 1987). C1 accuracy (or C2 accuracy) was submitted to a mixed-effect model on the fixed factors of *Radical Repetition* (repeated or unrepeated), *C1 Frequency* (HF-C1 or LF-C1), *Radical Function* (semantic or phonetic), and *C1 Duration* (43 ms, 57 ms, and 86 ms). The results of C1 accuracy is summarized below. The results of C2 accuracy were very similar to the results of C1 and C2 accuracy (reported in the main text), and a significant two-way interaction was the only exception. The results of C1 accuracy demonstrated that the accuracy was higher in the HF-C1 than in the LF-C1 condition (92.9% vs. 67.5%, $F(1,32) = 135.64$, $p < .001$). The accuracy increased with longer C1 duration (78.3%, 78.4%, and 84.0% for 43, 57, and 86 ms, respectively, $F(2,144) = 6.25$, $p < .005$). In summary, C1 frequency and C1 duration genuinely influenced participants' identification of C1s. The two-way interaction between C1 Frequency and C1 Duration were both significant in the analysis of C1 accuracy and C2 accuracy, though the pattern was reversed: in the results of C1 accuracy, the difference between HF-C1 and LF-C1 was smallest at the longest C1 Durations (25.4%, 29.2%, and 21.6% for 43, 57, and 86 ms, respectively, $F(2,4433) = 4.08$, $p < .05$), whereas in the results of C2 accuracy, the difference was largest at the longest C1 Duration (6.3%, 2.2%. and 12.8% for 43, 57, and 86 ms, respectively, $F(2,4433) = 5.48$, $p < .005$). The contradicting patterns may cancel each other out in the analysis of C1 and C2 accuracy. This result suggests that C1 accuracy and C2 accuracy are not independent of each other.

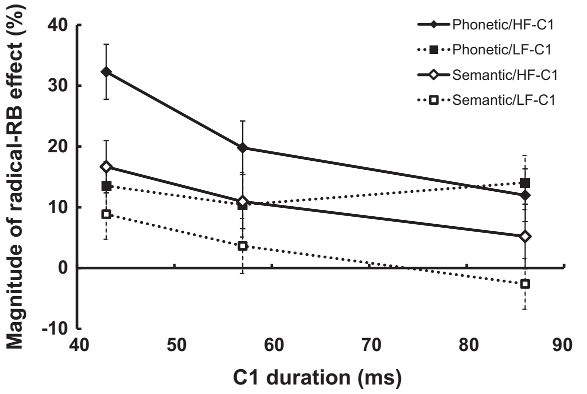

Fig. 4. The mean magnitude of radical-RB effect (unrepeated–repeated) in Experiment 1. The error bars indicate ±1 standard error of the means.

duration conditions of 43, 57, and 86 ms were (93.0%, 63.5%), (93.3%, 63.9%), and (96.1%, 64.2%), respectively. In the response of C2, the participants rarely filled in the un-presented radical that happened to make the original character (i.e., they added 几 on the right side of 食, which made the character 飢). The proportions of such responses of total errors across three C1 duration conditions of 43, 57, and 86 ms were 5.6%, 4.0%, and 4.2%, respectively. It should be noted that even if the participants occasionally filled in the repeated radicals in the critical trials when RB did occur, we would have only underestimated the magnitude of the radical-RB effect.

Discussion

In Experiment 1, four main findings are summarized below: first, the radical-RB effect was reliably observed. Further evidence comes from the explicit radical-RB: when participants made errors, they sometimes missed the repeated radical or replaced it with another radical. Second, the magnitude of radical-RB effect was reduced when C1 duration was increased, which replicates a typical RB effect (Kanwisher, 1987). Third, the radical-RB effect was observed in both HF-C1 and LF-C1 conditions, which suggests that characters were decomposed irrespective of character frequency. In addition, the magnitude of RB was larger for HF-C1 than for LF-C1, which is consistent with the findings by Bavelier et al. (1994) about modulation of word frequency on letter-cluster RB effect for English words. Finally, we found that radical-RB effect was observed for both semantic and phonetic radicals, and the magnitude of RB was larger for phonetic radicals than for semantic radicals.

The lower accuracy between two characters that share a radical in the present study can be accounted for by radical-RB effect based on two results. First, the radical-RB effect was decreased when the SOA between C1 and C2 was longer (i.e., the longer C1 duration in the present study). This pattern is consistent with the RB effect resulting from sub-lexical representations (see Harris & Morris, 2001; Yeh & Li, 2004). Second, explicit radical-RB was observed more often in the repeated than unrepeated trials. That is, only the repeated radical was omitted while the residual radical was not (see Harris & Morris, 2000).

We demonstrated here that both HF and LF characters were decomposed into radicals and hence gave rise to radical-RB effect. This result is not consistent with the prediction of the hybrid hypothesis that only LF characters are decomposed, or the holistic hypothesis that characters are not decomposed and the effect is due to character-level inhibition. The RB paradigm therefore provides stronger evidence for the analytic hypothesis of Chinese character processing as compared to CDT.

Two types of orthographic inhibitory effects have been reported in studies of Chinese characters and English words: RB for repeated sub-lexical representations (i.e., radical-RB in Chinese and letter-cluster RB in English), and character-level inhibition. These two types of orthographic inhibitions, though hard to tease apart, have different time-course patterns: RB for sub-lexical units occurs at short SOAs and the magnitude is reduced at longer SOAs (Harris & Morris, 2001; Yeh & Li, 2004). On the other hand, the character-level inhibition is suggested to be larger with longer SOA instead (see Chialant & Caramazza, 1997). Previous studies of Chinese character processing have reported inhibitory effects between orthographically-similar prime and target when their SOA was within the range of 43–57 ms (Chen & Shu, 2001; Perfetti & Tan, 1998; Wu & Chou, 2000). These studies did not aim to investigate the possible mechanism underlying the inhibition between orthographically-similar characters.[6] According to our current result, we suggest that the inhibition between characters sharing the same radical that has been reported in the literature should be partly attributed to the radical-RB effect rather than simply the character-level inhibition (e.g., Wu & Chen, 2003). This argument will be further supported by the result of Experiment 2.

The finding of larger magnitude of RB in the HF-C1 than in the LF-C1 condition is consistent with Bavelier et al.'s (1994) results in English. Character (or word) frequency is one of the most dominant factors in visual Chinese character (or word) recognition (e.g., Liu et al., 1996; Monsell, 1991). Given that radical-RB is sensitive to character

[6] One may wonder whether the results in the present study concerning the orthographically similar characters are consistent with findings of previous studies. Note that the stimulus pairs of orthographic prime and target used by Chen and Shu (2001) and Perfetti and Tan (1998) (called *graphic prime* in their papers) include both pairs sharing a radical (e.g., 斯 and 期) and pairs sharing strokes (e.g., 亦 and 示). It is difficult to further examine whether the orthographic inhibitory effects that they observed were due to radical-RB or character-level inhibition. In Wu and Chou's (2000) study, the prime shared a radical with the target in the orthographically similar condition (called *graphic prime*). In their Experiment 2, with similar time course that was used in the present study (50 ms and 85 ms prime-target SOAs), they observed that the orthographic effects in the CDT elicited by a HF prime were inhibitory (52 ms and 68 ms for the 50 and 85 ms SOAs as compared to control, respectively) while those by LF prime were facilitatory (−51 ms and −6 ms for the 50 and 85 ms SOAs, respectively). It is unclear how the character frequency of primes plays a critical role to elicit an inhibitory or facilitatory effect in their study, perhaps being dependent on whether the prime had been recognized (cf. Humphreys et al., 1987). It should be noted that these three studies aimed to probe the time courses of orthographic, phonological, and semantic activations, and hence they did not focus on the source of orthographic inhibitory effects as we do in the present study.

Table 1
The proportion of explicit radical-RB (%) and the results of *t*-test (one-tailed) in Experiment 1 (a) in the repeated (R) and unrepeated (UR) trials; (b) in C1 or C2 in the repeated trials.

C1 Duration											
43 ms				57 ms				86 ms			
(a)											
R	UR	*t*(47)	*p*	R	UR	*t*(47)	*p*	R	UR	*t*(47)	*p*
15.1	5.2	7.85	<.001	12.7	5.9	4.42	<.001	10.9	5.1	4.43	<.001
(b)											
C1	C2	*t*(47)	*p*	C1	C2	*t*(47)	*p*	C1	C2	*t*(47)	*p*
5.1	10.3	3.66	<.001	4.7	8.1	2.99	<.005	3.3	7.8	3.84	<.001

frequency, the radical-RB reported here should occur *during* the processing of character identification (Bavelier et al., 1994, p. 1441), rather than a perceptual effect that does not rely on accessing internal radical representations (e.g., RB for novel objects, see Coltheart, Mondy, & Coltheart, 2005). A radical binding model that accounts for the modulation of character frequency based on the mechanism of RB will be proposed in the General Discussion.

We also found that the radical-RB effect was robustly observed for both semantic and phonetic radicals, and the magnitude was larger for phonetic radicals than for semantic radicals. In the following experiments, however, the radical-RB effect was robust but there was no difference in the RB effects on semantic and phonetic radicals. We thus consider it premature to argue for any different representations between semantic and phonetic radicals in terms of their functions.

Experiment 2

Some Chinese characters, such as 悅, consist of the semantic radical (忄) with three strokes, and is smaller than the phonetic radical (兌) that has seven strokes. Hence, the C1–C2 pair with a repeated semantic radical (e.g., 悅 and 悟) would be less similar in orthography at the character level (due to less common strokes in the two characters) than the pair with a repeated phonetic radical (e.g., 悅 and 脫). In Experiment 2, we manipulated the proportion of the repeated radical (either the semantic or phonetic radical) relative to the unrepeated radical in a character, to examine whether this factor modulates the magnitude of the radical-RB effect.

The proportion of semantic and phonetic radicals is defined by the stroke count of a radical divided by the stroke count of a whole character. We compared the radical-RB effect for characters with a smaller semantic radical (such as 悅) to those with a larger semantic radical (such as 點). A genuine radical-RB effect should *not* be affected by the proportion of the repeated radical since it is one radical missing and the other intact when radical-RB occurs.

The account of character-level inhibition (e.g., Wu & Chen, 2003), on the other hand, would predict that the inhibitory effect systematically changes with the proportion of the repeated radical: the larger proportion the repeated radical is, the larger the magnitude of the inhibitory effect. Semantic-radical-RB would be larger than phonetic-radical-RB when the semantic radical has a larger proportion in a character, and the reverse pattern would be observed when the semantic radical has a smaller proportion in a character.

Method

Two new groups of 42 volunteers from the same pool of participants as in Experiment 1 took part in this experiment. Three factors, *Radical Repetition* (semantic-radical repeated, phonetic-radical repeated, and unrepeated), *Proportion of Semantic Radical* (small or large, and the proportion of phonetic radical was accordingly to be large or small, respectively), and *C1 Duration* (43 or 57 ms), were manipulated. The former two were within-participants factors, and each group of participants was tested with either one of the C1-duration condition.

Two types of characters, either consisting of a small semantic radical and a large phonetic radical, or vice versa, were selected. There were 27 characters selected in each type (see Appendix B). The mean proportion of semantic radicals was 29.9% in the semantic-radical small condition, and 68.1% in the semantic-radical large condition ($t(52) = 24.30$, $p < .0001$). Only two C1 durations, 43 and 57 ms, were tested because radical-RB effect was reliable in these two conditions in Experiment 1 (see Fig. 4).

Nine of the above mentioned 27 characters in each type (semantic-radical small or large) were chosen as C2. The character frequency and stroke counts of C2 in these two conditions were not significantly different ($ps > .05$). Each C2 was paired with three kinds of C1: characters share the same semantic radical, characters share the same phonetic radical, and characters consist of different radicals (i.e., the unrepeated condition). The character frequency and stroke counts for these six types of C1 (3 Radical Repetition × 2 Proportion of Semantic Radical) was not significantly different ($ps > .05$). The factor of Radical Repetition was in a yoked design, giving rise to three versions. There were 18 trials, three trials for each Proportion of Semantic Radical × Radical Repetition conditions, as well as nine filler trials in each version (see Method in Experiment 1). The presentation order of these 27 trials was completely randomized. Fourteen people participated in each version. Other details were identical to Experiment 1.

Results

The participants' accuracy when correctly reporting both C1 and C2 was calculated (Fig. 5). A mixed-effect

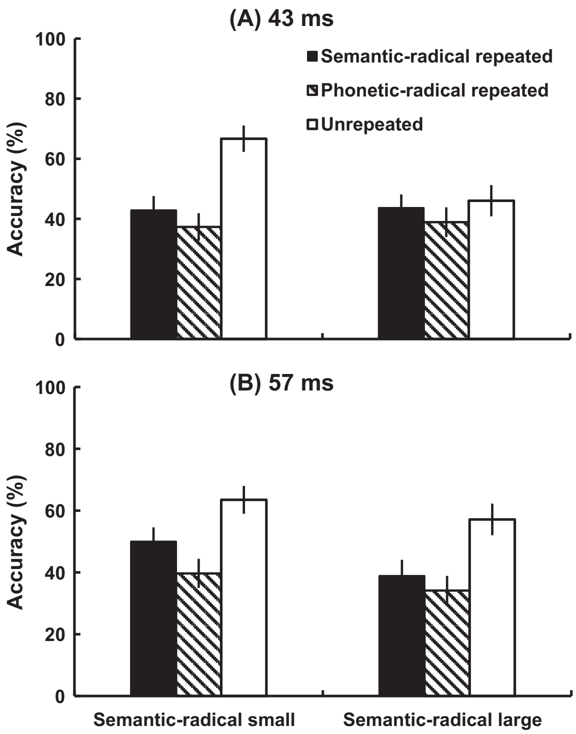

Fig. 5. The mean accuracy of participants' character identification performance (both C1 and C2 were correct) in Experiment 2, where C1 was presented for (A) 43 ms; and (B) 57 ms. The error bars indicate ±1 standard error of the means.

model was conducted on the fixed factors of Radical Repetition, Proportion of Semantic Radical, and C1 Duration. The main effect of Radical Repetition was significant ($F(2,18) = 14.67$, $p < .001$). The results of *post hoc t-tests* (Bonferroni correction) revealed that the accuracy was higher in the unrepeated condition than in the semantic-radical repeated condition (58.3% vs. 43.8%, $p < .001$), as well as than in the phonetic-radical repeated condition (58.3% vs. 37.5%, $p < .001$); these results indicate radical-RB effects for both semantic and phonetic radicals. However, there was no significant difference between the semantic-radical repeated and the phonetic-radical repeated conditions ($p = .11$), though there was a trend that the accuracy was always higher in the semantic-radical repeated condition than in the phonetic repeated condition. The main effect of Proportion of Semantic Radical was also significant ($F(1,18) = 4.51$, $p < .05$), which is due to the higher accuracy when the semantic radical was small rather than large (50.0% vs. 43.1%). The three-way interaction was marginally significant ($F(2,906) = 2.76$, $p = .06$). In the four Proportion of Semantic Radical × C1 Duration conditions, the main effect of Radical Repetition was significant ($Fs > 6.64$, $ps < .005$), except the semantic-radical large/43 ms condition ($F < 1$, $p = .53$). Note that the interaction between the factors of Radical Repetition and Proportion of Semantic Radical was not significant ($F = 1.25$, $p = .31$). That is, the relative proportion of repeated radical did not systematically modulate the magnitude of radical-RB effect.

Discussion

In Experiment 2, we manipulated the proportions of repeated radicals within a character defined by the stroke count of the radical divided by the stroke count of the character. The results revealed that the radical-RB effect was significant; however, the magnitude did not change with the proportion of the repeated radical (see similar results of letter-cluster RB in English words in Harris & Morris, 2004, Experiment 2). Hence, the effect reported in Experiment 2 should be attributable to the fact that the repeated radical was unseen (i.e., a genuine radical-RB effect), rather than the character-level inhibition.

One may notice that there was no radical-RB effect when the C1 duration was 43 ms in the condition where semantic radicals occupied a large proportion. Note that the optimal condition to demonstrate RB is 50–85% accuracy in the unrepeated condition (see Harris & Morris, 2004, p. 313). The failure to obtain a significant radical RB effect in this semantic-radical large/43 ms condition may be attributable to the low accuracy in the unrepeated condition (46.0%), which was not significantly different from the other two radical repeated conditions. It seems that the C1 duration of 43 ms was too short for participants to identify characters that consisted of a large semantic radical and a small phonetic radical – this also explains the main effect of the lower accuracy for this type of characters than the other type that consists of a small semantic radical and a large phonetic radical.

This result can be accounted for by Taft and Zhu (1997)'s notion that Chinese characters, similar to English words, are processed from left to right when the two radicals are arranged horizontally. When the left radical is large (that happened to be a semantic radical in this experiment), it consists of more strokes and it may therefore take longer to bind these strokes to construct the radical. Note that Taft and Zhu assume that the bottleneck for character processing lies in the right radical in terms of RT measure in CDT (see Fig. 2 in their paper), whereas we suggest that the bottleneck lies in the left radical in terms of an accuracy measure (in which the presentation time of the character is limited). If the time required for binding strokes to construct the left radical is long, the character would be less likely to be recognized in time before its offset. Whether the left or right radical constitutes the bottleneck in Chinese character recognition in different measures indicates that the radical is the basic processing unit.

Experiment 3

In the final experiment, we examine whether radical combinability influences the radical-RB effect. Radical combinability has been demonstrated to modulate participants' performance in CDT: time required to respond to a character was shorter when the character contained a high-combinability radical than one of low-combinability (Feldman & Siok, 1997; Taft & Zhu, 1997). This advantage of high-combinability radicals can be attributed to their high occurrence and familiarity.

Two possible predictions about how radical combinability influences a radical-RB effect can be proposed. It is possible that high-combinability radicals are more easily segregated than low-combinability ones, thus giving rise to a larger radical RB effect. Such a result would support the hybrid hypothesis that radicals are not necessarily represented as independent units. On the other hand, if radicals serve as processing units and are always represented, then the radical-RB effect should be always observed and its magnitude should be similar for high- and low-combinability radicals. This result would support the analytic hypothesis. These two possibilities are examined in Experiment 3A.

Not only the combinability of the repeated radical, but also that of the residual radical (the radical *D* in Fig. 1), may modulate the magnitude of RB. Harris (2001) demonstrated that, after the RB for repeated letters had occurred (e.g., the letters <u>we</u> in the pair of <u>we</u>*ight* and <u>we</u>*apon*), the combinability of the residual letters (-<u>apon</u> in this example) would influence the magnitude of RB effect. That is, when the residual letter can only construct a single word (such as <u>apon</u> only appearing in *we*<u>apon</u>), the participants would be more likely to reconstruct the correct word (i.e., *weapon*) than when the residual letter constructs more than one word. We therefore examined whether the combinability of residual radicals modulates the reconstruction process after RB occurs in Experiment 3B.

Experiment 3A

Method

A new group of 30 volunteers from the same pool of participants as in Experiment 1 took part in this experiment. Three factors, *Radical Repetition* (repeated or unrepeated), *Radical Function* (semantic or phonetic), and *Radical Combinability* (high or low), were manipulated. Radical combinability was calculated in terms of the number of characters in which a given radical appears, regardless of its function (Taft & Zhu, 1997).[7] The radical combinability includes the number of characters for a radical serving as a semantic radical in Chinese dictionary (2000) and serving as a phonetic radical in Liu et al. (2001). Because the combinability of semantic radicals is much higher than for phonetic radicals, the criteria to classify as high- or low-combinability for semantic and phonetic radicals were different: for semantic radicals, a combinability at or above 50 characters was considered high; for phonetic radicals, a combinability at or above 10 was high.

Twenty C2s were selected in each of the four Radical Function × Radical Combinability conditions (see Appendix C). The character frequencies of C2 were matched for the four conditions ($ps > .9$). There were, however, differences between their character stroke counts.[8] Each C2 was paired with two kinds of C1: one shared a radical (the repeated condition) and the other did not (the unrepeated condition). The character frequency and stroke counts of repeated and unrepeated C1 were matched (all $ps > .8$). The factor of Radical Repetition was in a yoked design, giving rise to two versions of stimulus list. In each version there were 80 trials presented in a randomized order for each participant. Each version was tested with 15 participants. All of the items in the RSVP stream were presented for 43 ms.

Results

The participants' performance in terms of accuracy when C1 and C2 were both correct is shown in Fig. 6A. A mixed-effect model was conducted on the fixed factors of Radical Repetition, Radical Function, and Radical Combinability. The radical-RB effect was significant as the accuracy was higher for the unrepeated trials than for the repeated ones (58.9% vs. 43.4%; $F(1,85) = 19.79$, $p < .001$). None of any other main effects or interactions were significant (all $Fs < 1$, $ps > .43$). In summary, the radical-RB effect was robustly observed irrespective of the combinability of the repeated radical, and the magnitudes of radical-RB effects for high and low combinability radicals were similar.

Experiment 3B

Method

A new group of 28 volunteers from the same pool of participants as in Experiment 1 took part in this experiment. Two factors were manipulated: *Radical Repetition* (repeated or unrepeated) and *Residual Radical Function-Combinability* (semantic-high, semantic-low, and phonetic-low). All residual radicals used in this experiment were simple characters by themselves, which means that they were a character without binding to another radical and participants did not need to fill in another radical to make a character. It was difficult to find enough radicals to construct a 2 × 2 (Radical Function and Radical Combinability) design. Furthermore, the criterion to separate high- vs. low-combinability radicals had to be altered because a new set of radicals was used: semantic-radical combinability above 45 was considered high. The phonetic-radical combinability was below 20 (the phonetic-low condition). See Appendix D for the stimulus materials.

Each of the three conditions contained 10 stimulus sets. The factor of Radical Repetition was in a yoked design, giving rise to two versions of the stimulus list. In each version, there were 30 critical trials, of which half were repeated. In addition to the 30 trials, 10 filler trials were added (see Method in Experiment 1). Each version was tested with

[7] Feldman and Siok (1997) calculated the radical combinability in terms of their radical function separately. In Experiment 3A of the present study, when keeping the criterion to categorize high- and low-combinability semantic (or phonetic) radicals constant, only four high-combinability phonetic radicals are now shifted to low-combinability ones. The results did not differ from those obtained from the analysis when the radical combinability was calculated irrespective of its function (reported in the main text).

[8] The mean character stroke counts in the *phonetic-radical high-combinability* condition is significantly lower than in the other three conditions, as indicated by the main effect of Radical Combinability ($F(1,76) = 4.295$, $p < .05$) and the interaction effect of Radical Function and Radical Combinability ($F(1,76) = 5.132$, $p < .05$). Nevertheless, this difference did not contribute to the main results given that the participants' accuracy in this condition was not significantly higher than the other three conditions.

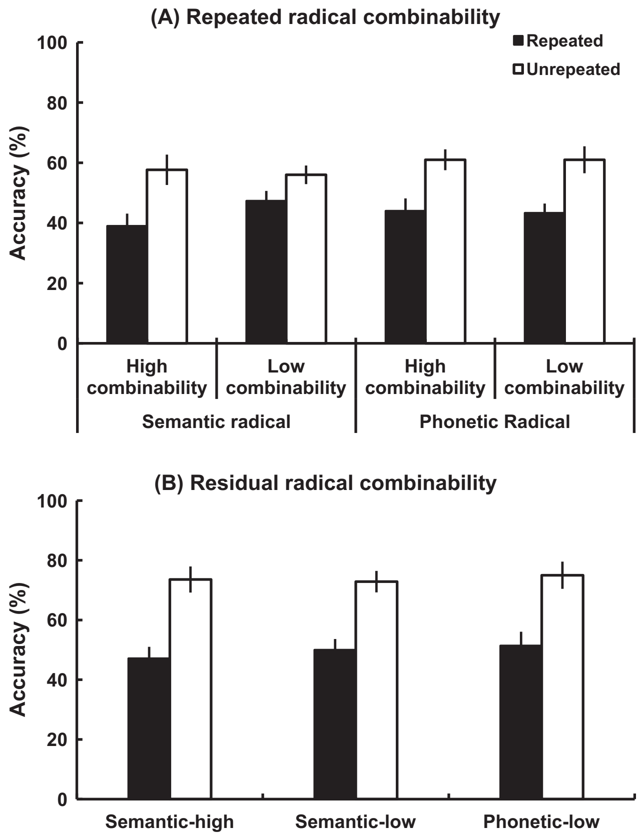

Fig. 6. (A) The mean accuracy of participants' character identification performance (both C1 and C2 were correct) in Experiment 3A, in which the combinability of the repeated radical was manipulated; (B) The mean accuracy of participants' character identification performance (C2 was correct) in Experiment 3B, in which the combinability of the residual radical was manipulated. The error bars indicate ±1 standard error of the means.

14 participants. All of the items in the RSVP stream were presented for 43 ms. The stimuli were presented on a 17-in. calibrated EIZO color monitor.

Results

Given that C2 is the item where the repeated radical is presumably missed when RB occurs (Kanwisher, 1987), the process to fill the missing radical should take place at C2 (see Harris, 2001). We therefore focused on the accuracy of C2 in Experiment 3B in order to verify whether the residual radical combinability would influence the reconstruction rate of C2 (see Fig. 6B). A mixed-effect model was conducted on the fixed factors of Radical Repetition and Residual Radical Function-Combinability. The radical-RB effect was significant: the accuracy was higher in the unrepeated than in the repeated condition (73.8% vs. 49.5%; $F(1,30) = 16.36$, $p < .001$). Neither the main effect of Residual Radical Function-Combinability, nor their interaction, was significant ($Fs < 1$, $ps > .95$). The proportion of the explicit radical-RB in each condition is reported in Table 2. In summary, the radical-RB effect was significant and the magnitude was not affected by the combinability of the residual radicals.

Discussion

We manipulated the combinability of the repeated radicals in Experiment 3A, and the combinability of the residual radicals in Experiment 3B. The results demonstrate a robust RB effect for radicals in all conditions. In addition, the magnitude was neither affected by the combinability of the repeated radical (Experiment 3A), nor by the combinability of the residual radical (Experiment 3B). That is, both high- and low-combinability radicals are represented as independent units. Hence, we suggest that by utilizing the RB paradigm to examine the processing of Chinese characters, the analytic hypothesis is supported.

Table 2
The proportion of explicit radical-RB (%) in the repeated (R) and unrepeated (UR) trials and the results of *t*-test (one-tailed) in Experiment 3B.

Semantic-high				Semantic-low				Phonetic			
R	UR	*t*(27)	*p*	R	UR	*t*(27)	*p*	R	UR	*t*(27)	*p*
9.3	1.4	2.64	<.01	6.4	0	2.78	<.005	18.6	6.4	2.92	<.005

The results in Experiment 3B exclude the possibility that the low-combinability residual radical might help participants correctly guess the original C2 after RB had occurred. Note that in Harris' (2001, Experiment 2) study, she manipulated the mean combinability of residual letter cluster at one vs. six, and none of them stood alone as a word. Hence, it is certainly easier for their participants to complete the correct word by its fragments when there is only one possibility as compared to multiple alternatives. However, radicals in Chinese characters always occur in more than one character (Taft & Zhu, 1997). We therefore suggest that the magnitude of radical-RB effect in Chinese character is not sensitive to the combinability of the residual radical.

General discussion

In the present study, we examined the analytic, holistic, and a hybrid hypothesis of Chinese characters processing by testing whether radicals are necessarily represented. We utilized the radical-RB effect which is a phenomenon first reported by Yeh and Li (2004). As an extension of that study, we observed the following results: (1) a genuine RB effect was observed for radicals embedded in both HF and LF characters; (2) the radical-RB effect was susceptible to character frequency, which indicates that the effect occurred during the processing of character recognition; and (3) the magnitude of radical-RB effect was not sensitive to the proportion of the repeated radicals relative to that of the unrepeated radicals (Experiment 2), nor to the combinability of repeated or residual radicals (Experiment 3). Taking these findings together, we suggest that characters are necessarily decomposed into radicals during the process of character recognition.

The radical-RB effects obtained in the present study, combined with the results reported by Yeh and Li (2004), provide empirical evidence for an analytic hypothesis of Chinese character processing: Yeh and Li demonstrated that radical-RB occurs earlier in time-course than does character-RB. In the present study we demonstrate that radical-RB is reliably observed when manipulating character frequency, radical function, radical proportion, and radical combinability. These results are consistent with the analytic view, rather than the holistic view (as shown in Experiments 1 and 2) or the hybrid view (Experiments 1 and 3). We therefore suggest that the radical-level analysis is an indispensable mediator for the orthographic processing of Chinese character recognition. Even though the recognition of HF characters is rapid, it still depends on radicals' binding (see Hsiao & Cottrell, 2009). Indeed, several aspects of the nature of radicals indicate that they are very likely to be the basic units of character processing: radicals are simple and familiar units numbering into the hundreds; combining the radicals into various compound characters makes it possible to recognize 4000–5000 daily used characters.

In previous CDT studies, the analytic hypothesis of Chinese character processing was not fully supported because RTs were similar when HF characters contained a high-combinability radical or a low-combinability radical (e.g., Ding et al., 2004; Li & Chen, 1999; Zhu & Taft, 1994). Utilizing the RB paradigm that relies on participants' accuracy of performance is a more sensitive measure since this method probes whether the radical is represented or not, rather than the processing time of radicals. We then accompany our results of Chinese character processing by proposing a model based on the mechanisms underlying RB (Bavelier, 1994, 1999; Kanwisher, 1987, 1991). The reported results and the proposed model in this study are both in line with the analytic view of Chinese character processing.

The type-token model for binding radicals in Chinese character recognition

The type-token model proposed by Kanwisher (1987, 1991) most prominently addresses the phenomenon of RB. According to this model, each item in RSVP activates two kinds of representations: *type* is the pre-existing long-term representation for recognition, and *token* is the spatiotemporal representation used to label the occurrence of the event. In order to successfully report a visual event, the activated type has to link to its associated token (Kanwisher, 2001). However, there is a limitation to the type-token binding process: a given type is unable to bind to multiple tokens presented within a short interval, thereby causing the phenomenon of "blindness" to the second occurrence of a repeated item (e.g., Chun, 1997; Chun & Cavanagh, 1997; Morris & Harris, 1999; Park & Kanwisher, 1994; Schendan, Kanwisher, & Kutas, 1997; Wong & Chen, 2009).

Our hypothetical mechanism for the occurrence of radical RB is demonstrated in Fig. 7. Here we use an RSVP trial with *IR* 星, *C1* 站, and *C2* 帖 as an example (see the bottom panel). When the radical type "占" is linked to the second token corresponding to C1 "站" (the thick solid line in Fig. 7), it is unable to link to the third token corresponding to C2 "帖" within a short interval (the dotted line in Fig. 7). This failure of type-token binding leads to only the radical "巾" being tokenized in the third token, thus giving rise to a radical-RB effect. On the other hand, in the priming paradigm, if C1 is not required to report, the radicals of C1 do not need to be linked to its token. Hence, the repeated radical "占" can be tokenized in C2. In addition, given that the type of the repeated radical "占" has been activated by C1, it may facilitate the processing of C2, giving rise to an orthographic priming effect (Humphreys et al., 1987). This type-token binding model can explain the facilitatory effect induced by the repeated radical in the priming paradigm (Ding et al., 2004; Feldman & Siok, 1999a) and the inhibitory effect in the RB paradigm.

Although this type-token hypothesis is proposed to account for the radical-RB effect reported in the present study, such a framework of radical binding can also be used to explain the radical-based illusory character phenomenon (Fang & Wu, 1989; Saito, Masuda, & Kawakami, 1998). In this phenomenon, observers were likely to perceive an illusory character by combining radicals that were presented in different characters when their attentional resource was otherwise occupied. For example, when the characters "松" and "咬" were presented, participants

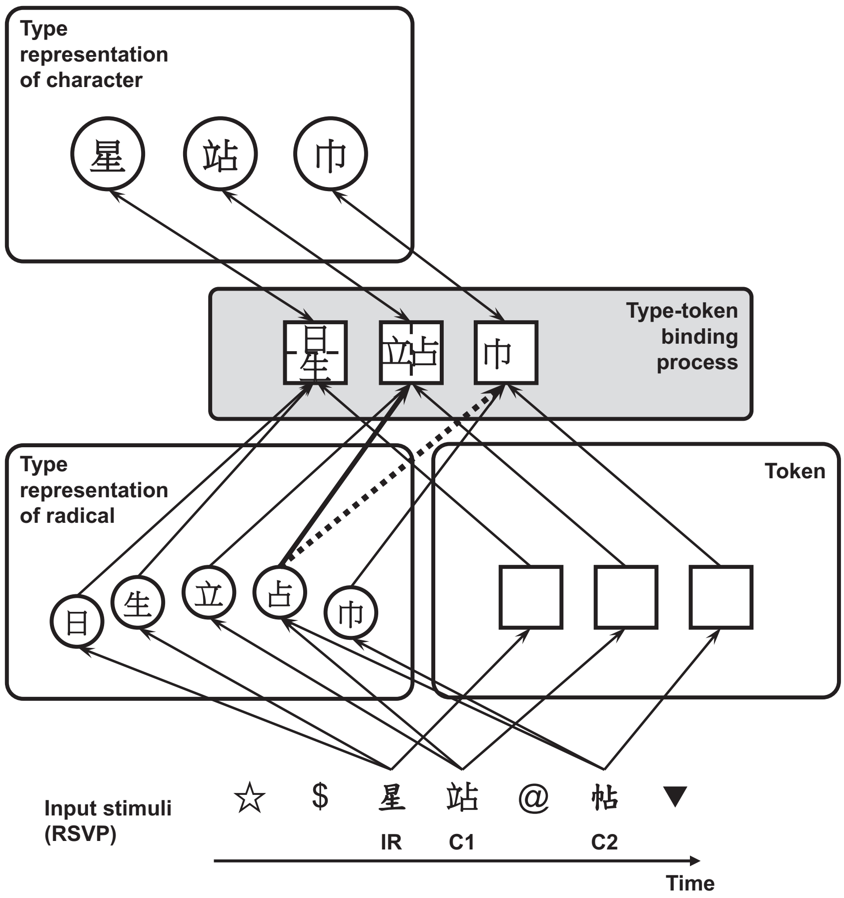

Fig. 7. The radical binding model of Chinese character recognition. The type representations (circles) and token representations (squares) of each character are both activated. The radical *types* of each character are activated and linked to correspondent *tokens* in order to construct the character representations.

sometimes reported the character “校” as a result of incorrectly binding the left radical “木” in 松 and the right radical “交” in 咬. The radical RB effect results from the failure to bind one radical type into two tokens, whereas the illusory character phenomenon is caused by incorrectly binding two radical types into one token (Kanwisher, 1991). Radical-RB effect and the radical-based illusory character phenomenon are the two facets of the radical binding mechanism.

The influence of character frequency in the type-token binding model

Our model depicted in Fig. 7 uses the original form of Kanwisher’s type-token model of RB (Kanwisher, 1987). However, in order to adequately explain the modulation of character frequency, we incorporate a later model proposed by Bavelier (1994, 1999). She suggests that RB is not only caused by the failure to link a type to a token but also by the failure to consolidate the bound types in the token, because only a stabilized token can be encoded into episodic memory for response. This two-stage model (including tokenization and consolidation) considers the RB effect to be a gradient determined by several factors, rather than an all-or-none phenomenon. Adding Bavelier’s two-stage model helps to explain the magnitude change of RB effect observed in the current study.

We suggest that the character frequency may serve as a top-down modulation of the *consolidation* process caused by the feedback from the character *type* to the *type-token binding process* (see the bidirectional connections in Fig. 7). We assume that the bound radicals in this process can activate the representation of a HF character rapidly (Forster & Chamber, 1973; Liu et al., 1996), and, in turn, the character representations can send feedback to consolidate the binding process. In Experiment 1, we manipulated C1 as HF or LF characters while C2 was always intermediate in character frequency. The feedback sent from the character representation to its associated bound token should be strongest for HF-C1, intermediate for medium-frequent C2, and weakest for LF-C1. The binding process of the C2 should thus be less consolidated than the HF-C1 while stronger than the LF-C1. As a result, C2 may more easily lose the link to the type of repeated radical when it follows HF-C1 (i.e., a larger radical-RB effect) than when it follows LF-C1 (i.e., a smaller radical-RB effect), which leads to a larger radical-RB effect in the HF-C1 than in the LF-C1 condition.

Implementing the type-token binding in Chinese character processing models

Taft and colleagues (Taft, 2006; Taft, Zhu, & Ding, 2000) proposed an interactive-activation model that fit the analytic view in order to account for the orthographic processing of Chinese characters. This model constitutes four hierarchical levels: strokes, radicals, characters, and words. The representations at the lower level send activations to the linked representations at the higher level, whereas the representations at the same level may inhibit each other if they receive the same activation from the lower level. Taking the character 楓 as an example, the character is activated by the constituent radicals of 木 and 風, and the activated 楓 may inhibit the character 松 given that the two characters share the same semantic radical 木 on the left.

According to the interactive-activation model (Taft, 2006), the target character (e.g., 楓), presumably, is the one receiving the strongest activation from the radical representations (i.e., 木 and 風). This model cannot explain the occurrence of radical RB as reported in the current study. We also consider this activation mechanism inefficient for rapid access of character representation when the character consists of a high-combinability radical, since such a radical would activate a large number of candidate characters. Furthermore, it needs to be considered that, in daily life, we rarely see a character standing-alone but usually read a string of characters. Given that we need to process multiple characters rapidly and accurately, certain spatial (see Taft, 2006) and temporal constraints to bind radicals in order to activate a particular character are needed. For example, when reading the character string of 星, 站, and 帖, the radical "日" will bind with the radical "生", because both radicals belong to the event of the first character, rather than with the radical "立" that is presented in the second character. We suggest the *token* representation serves the function of providing both spatial and temporal constraints on binding radicals, since it signals the episodic information of a given stimulus.

Whether radical function is represented during Chinese character processing

Semantic and phonetic radicals presumably serve different functions by either conveying the meaning or the pronunciation of the whole character. Chen and Allport (1995) were the first to demonstrate that semantic radicals only influence participants' performance in semantic comparison task, and that phonetic radicals only influence participants' performance in phonological comparison task. Numerous studies have separately investigated the functional roles of semantic radicals (Chen & Weekes, 2004; Feldman & Siok, 1999a, 1999b; Leck et al., 1995; Li & Chen, 1999; Yan, Zhou, Shu, & Kliegl, 2012) and phonetic radicals (Flores d'Arcais et al., 1995; Hue, 1992; Lee et al., 2004, 2007; Liu et al., 1996, 2003; Saito et al., 1998; Seidenberg, 1985; Tzeng, Lin, Hung, & Lee, 1995; Zhou & Marslen-Wilson, 1999). Until now, there seems to be no consensus about how the function of the radicals is implemented in Chinese character processing. Two currently influential models implement radical-level analysis occurring before character recognition while ignoring the role of radical function (see Perfetti, Liu, & Tan, 2005; Taft, 2006).

Even though a radical's function and position are highly correlated (Perfetti & Tan, 1999), it can still be manipulated independently. In order to better understand the interplay between the function and position representations of a radical, we can use the RB paradigm in future studies. For example, the position of repeated radicals can be held constant while their function is manipulated, or vice versa, and examined to see whether the radical-RB effect changes with the change of either radical function or position. The reduction of radical-RB due to the change of radical function or position would indicate that factor is encoded with radical representation (see Bavelier, 1994, 1999).

Comparing the processing of Chinese characters and English words

The nature of radical representations in Chinese characters, to date, can be summarized as follows: (1) both HF and LF characters are decomposed into radicals in the early processing stage (see Experiment 1); (2) radicals are encoded with their spatial position within a character (Ding et al., 2004; Taft & Zhu, 1997; Taft et al., 1999; though see Tsang & Chen, 2009) or their spatial configuration (Perfetti et al., 2005; Yeh, 2000; Yeh & Li, 2002; Yeh, Li, & Chen, 1999; Yeh, Li, Takeuchi, Sun, & Liu, 2003; Yeh et al., 1997); and (3) it is equivocal whether radical function is represented at this stage (see the previous section).

In the literature of English word processing, it has been demonstrated that a morpheme (such as *dark* in <u>*dark*</u>*ness*) is decomposed in the early processing stage (Longtin & Meunier, 2005; Marslen-Wilson, Bozic, & Randall, 2008; Rastle et al., 2004 for reviews, see Davis, 2004; Rastle & Davis, 2008). The nature of morphemic processing is similar to Chinese radicals because: (1) both HF and LF words are decomposed into morphemes (McCormick, Brysbaert, & Rastle, 2009); (2) the representation of a morpheme is position-sensitive (Crepaldi, Rastle, & Davis, 2010), (3) nevertheless, there is still a debate regarding whether morphemes at an early processing stage provide semantic information to the whole word (Dunabeitia, Perea, & Carreiras, 2008; Feldman, O'Conner, & Moscoso del Prado Martín, 2009) or not (Davis & Rastle, 2010; Marslen-Wilson et al., 2008; Rueckl & Aicher, 2008). Therefore, to date, it is suggested that the morphological processing before lexical access is based on orthographic analysis (called "morpho-orthographic" decomposition), but not necessarily on semantic analysis (called "morpho-semantic" decomposition).

It seems that radical representations in Chinese are similar to morpho-orthographic representations in English. The main challenge lies in how to compare four levels in Chinese (stroke, radical, character, and word) to three levels in English (letter, morpheme, and word). A Chinese character is typically defined as a morpheme since this is the level bearing the "minimal meaning units" (Chao, 1968; Hoosain, 1992; Taft & Zhu, 1997; Zhang & Peng, 1992). In the model proposed by Taft (2006), the orthographic representation of a character connects to a concept representation called *lemma*. The decomposition of characters into radicals is called "submorphemic processing" (Taft & Zhu, 1997), and the radical representations have no access to lemmas. Binding radicals to construct the characters as proposed in our Fig. 7 fits better into the orthography system of the model proposed by Taft (2006).

Taft (2003) proposed a similar model for English words that provides another possible way to represent radicals. For example, the word "policeman" is decomposed into three orthographic representations "pol", "ice", and "man", and then the associated lemmas is accessed in a hierarchically fashion: the orthographic representations "pol" and "ice" first conjointly access the lemma of "police",[9] and then combine with "man" to access the lemma of "policeman". The stage at which that "pol" and "ice" are represented is therefore similar to that of Chinese radical representation: given that the radicals "木" and "風" may have no corresponding lemmas, they can conjointly activate the lemma of character 楓 ([fong], "maple").[10] That is, after a radical is bound with another radical in the type-token binding process in Fig. 7, it will link to a lemma corresponding to the character (rather than an orthographic representation of the character). This possibility enables radicals to be the morpho-orthographic representation in Chinese writing system.

Conclusion

By utilizing the RB paradigm, we demonstrate that Chinese characters are decomposed at an early stage in processing. The results of the current study support the analytic hypothesis that radicals are independently represented and then bound to construct the character-level representations during recognition. This process is depicted in our radical binding model. Finally, we suggest that radicals can be considered as submorphemic representations as suggested by Taft and Zhu (1997), or alternatively, as morpho-orthographic representations in Chinese writing system.

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Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jml.2014.10.002.

[9] The orthographic representation of "ice" also activates the lemma "ice", but this lemma is not used to construct the lemma "police" which is activated conjointly with "pol" and "ice".

[10] Taft (2003) suggested that there is no need to have an orthographic representation level for the compound word such as "policeman", since "pol", "ice", and "man" are hierarchically constructed in the lemma system. Hence, the orthographic level of compound words is redundant and unnecessary. In a similar vein for Chinese, the hierarchical processing of character and word can be constructed in the lemma system if radical level in Chinese corresponds to the morpho-orthographic level in English.

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