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Sub-lexical phonological and semantic processing of semantic radicals: a primed naming study

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Abstract Most sinograms (i.e., Chinese characters) are phonograms (phonetic compounds). A phonogram is composed of a semantic radical and a phonetic radical, with the former usually implying the meaning of the phonogram, and the latter providing cues to its pronunciation. This study focused on the sub-lexical processing of semantic radicals which are themselves free standing sinograms. Two primed naming experiments were carried out to examine whether the meanings and pronunciations of the semantic radicals embedded in phonograms were activated or not

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during sinogram recognition. In Experiment 1, semantically opaque phonograms were used as primes. We observed facilitatory priming effects for targets which were semantically related to the semantic radicals embedded in primes, but not to the primes themselves. These effects were present for low-frequency primes, but not for high-frequency primes. Experiment 2 used only low-frequency phonograms as primes. We observed facilitatory priming effects for targets which were homophones of the semantic radicals embedded in primes, but not of the primes themselves. These results suggest that sub-lexical semantic and phonological information of semantic radicals are activated, and that the activation processes are modulated by the lexical frequency of the host phonograms. Our study shows that sub-lexical processing of semantic radicals is similar to that of phonetic radicals, indicating no fundamental difference between sub-lexical processing of semantic and phonetic radicals, supporting the view that a radical has a unique representation irrespective of its function in the orthographic system of Taft's model.

Keywords Orthography · Phonology · Primed naming · Semantics · Semantic radical

Introduction

A central question in psycholinguistic research concerns the types of information stored in the mental lexicon. Concerning the Chinese mental lexicon, researchers have reached a consensus that Chinese characters, that is, sinograms (Wang & Tsai, 2011) have representations at lexical level (Perfetti, Liu, & Tan, 2005; Taft, 2006; Zhou, Shu, Bi, & Shi, 1999). However, whether and how sub-lexical information, that is, radicals and strokes, might be represented in the mental lexicon are still open issues.

Orthography of Chinese sinograms

In Chinese, there are two types of sinograms: *simple sinograms*, which have only one orthographic component, and *compound sinograms*, which have more than one orthographic component. As many as 80 % of sinograms are phonograms (Zhou, 1978), that is, phonetic compounds, which consist of two functional components: a semantic radical, which usually implies the meaning of its host sinogram, and a phonetic radical, which provides cues to the pronunciation of its host sinogram. For example, the phonogram, 矿, *kuang4,*[1] meaning *mineral*, is comprised of a semantic radical, 石, *shi2*, meaning *stone*, and a phonetic radical, 广, *guang3*, meaning *broad*. The phonograms with left–right structure which have semantic radicals on the left and phonetic radicals on the right (e.g., 矿) are described geometrically as

[1] The letters represent the official Romanization of standard Chinese, that is, Pinyin, while the number indicates the corresponding tone.

SP (S and P stand for semantic and phonetic radicals respectively). Phonograms with their phonetic radicals on the left and semantic radicals on the right (e.g., 顶, *ding3*, meaning *top*) are described geometrically as PS (Wang & Tsai, 2011). According to an analysis of Chinese compound database (Hsiao & Shillcock, 2006), among the most frequently used 3027 compound sinograms, about 72 % of them are left–right structured. Moreover, 90 % of the left–right structured sinograms are SP sinograms (see also Feldman & Siok, 1999).

A phonogram whose pronunciation is the same as that of its phonetic radical (ignoring tonal difference) is called a *regular sinogram*, or else an *irregular sinogram* (Lee, Tsai, Su, Tzeng, & Hung, 2005). For example, the phonogram 植 (*zhi2*, meaning *plant*) which shares an identical pronunciation with its phonetic radical 直 (*zhi2*, meaning *vertical*) is a regular sinogram. In contrast, the phonogram 贻 (*yi2*, meaning *present*) whose pronunciation differs from that of its phonetic radical 台 (*tai2*, meaning *platform*) is an irregular sinogram. Similarly, a phonogram whose meaning differs entirely from that of its semantic radical is called a *semantically opaque* sinogram (e.g., 弥, *mi2*, meaning *full*, containing the semantic radical 弓, *gong1*, meaning *bow*), whereas a phonogram whose meaning is closely related to that of its semantic radical is called a *semantically transparent* sinogram (e.g., 植, *zhi2*, meaning *plant*, containing the semantic radical 木 *mu4*, meaning *wood*) (Chen & Weekes, 2004). Moreover, some radicals, for example, 木, are free standing sinograms. A subset of such radicals can function as either semantic or phonetic radicals in different compound sinograms. For instance, the semantic radical 石 of the SP sinogram 矿 functions as the phonetic radical in another PS sinogram 硕, *shuo4*, meaning *large*.

Models of Chinese word reading

Derived from connectionist structure of lexical representation (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989), the generic model proposed by Zhou and his colleagues (Zhou, et al., 1999) emphasizes the predominant role of orthography in initial lexical access and assumes that all orthographic forms of Chinese morphemes, whether they are sinograms, phonetic or semantic radicals, are represented at the same level in the mental lexicon (Zhou & Marslen-Wilson, 1999b). These orthographic representations have direct links with representations in both phonological and semantic systems. Another special assumption is that in reading compound sinograms, the visual input is automatically decomposed into different orthographic units which map in parallel to orthographic representations in the mental lexicon (Zhou & Marslen-Wilson, 1999b; Zhou, et al., 1999).

The lexical constituency model (Perfetti, et al., 2005) stresses the role of phonology and assumes that a word representation consists of three interlocking constituents: orthography, phonology and semantics. In this model, word identification entails the retrieval of all three constituents (Tan & Perfetti, 1998). As for the orthographic system in Chinese, the lexical constituent model represents orthographic units at both radical and lexical levels. Thus radicals which are themselves

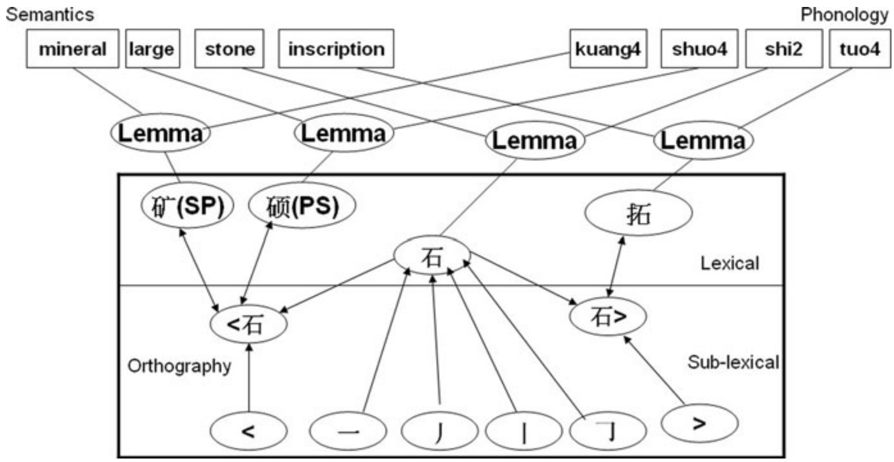

Fig. 1 Illustration of the orthographic system in Taft's model

free standing sinograms are represented at both radical and lexical levels (Perfetti, et al., 2005). However, in this speculation, how the representations of radicals connect to their corresponding phonology and semantics is not specified.

Taft and his colleagues proposed a further detailed hierarchical model (see Fig. 1) in which the orthographic system shares some similarity with the lexical constituency model, that is, radicals which are free standing simple sinograms are also represented at both lexical and radical level. Specifically, the hierarchical model adopts the interactive activation framework and assumes that there are three subsystems: orthography, phonology, and semantics (Taft, 2006). Their claims involve that (see justification in Ding, Peng, & Taft, 2004; Taft & Zhu, 1997; Taft, Zhu, & Ding, 2000): (a) simple sinograms and compound sinograms have their own lexical representations at different levels, with the latter higher than the former; (b) radicals that are constituents of sinograms are represented at the sub-lexical level; (c) there are different representations for radicals when they appear in different position.

The simple sinogram 石 itself has a lexical representation (see Fig. 1). In compound sinograms, for example, 硕 and 矿, the corresponding radical 石 appears in the left-side, so it has a left-side version representation. In another compound sinogram 拓, tuo4, meaning *inscription*, the radical 石 appears in the right-side position, so it has a right-side version representation. Representation of the simple sinogram 石 is activated by stroke features, while the corresponding radical representation is only activated when stroke configurations, that is, radicals, are found in the relevant position (i.e., left or right) of compound sinograms.

As shown in Fig. 1, the radical 石 in the SP sinogram 矿 functions as a semantic radical, whereas in the PS sinogram 硕 it functions as a phonetic radical. So there is a possible confound between the position of radicals and their functions. On one hand, the argument that representations of radicals are position-sensitive is challenged by other studies (e.g., Tsang & Chen, 2009). On the other hand, the study of Taft and Zhu (1997) which found combinability effect only for the radicals at the right-side position was challenged by Feldman and Siok (1997): It has been showed that, when combinability of semantic and phonetic radicals was counted separately, the combinability effect was robust for both left-side and right-side positions. Therefore Feldman and Siok (1997) argued that the function of radicals was overlooked in the study of Taft and Zhu (1997) and that the function of radicals was essential to any investigation on how visual units of sinograms were processed.

In summary, in these models of sinogram recognition, the function of radicals is not stressed and it may confound with the position of radicals. This issue is not addressed in the generic model. However, it is clear that Taft's model favors position-sensitive representations and does not emphasize the role of function. According to their claims, the processing of semantic and phonetic radicals is similar with each other. Specifically, for radicals which can be free standing sinograms, they should be processed similarly no matter whether they function as the semantic or the phonetic radicals in compound sinograms.

Previous studies on processing of radicals

In sinogram recognition, there is increasing evidence that reading a sinogram involves the processing of its radicals (Ding, et al., 2004; Feldman & Siok, 1997, 1999; Lee, Tsai, Chiu, Tzeng, & Hung, 2006a; Lee, Tsai, Huang, Hung, & Tzeng, 2006b; Taft & Zhu, 1997).

Concerning the sub-lexical processing of radicals, many researchers have taken the function (i.e., semantic or phonetic) of a radical into account. One line of research has examined the statistical characteristics of phonetic and semantic radicals (Chen & Weekes, 2004; Feldman & Siok, 1999; Hsiao, Shillcock, & Lavidor, 2006; Hsiao, Shillcock, & Lavidor, 2007; Lee, et al., 2006b; Lee, et al., 2005). For example, the *consistency*[2] and *combinability*[3] of phonetic radicals were demonstrated to influence sinogram naming (Hsu, Tsai, Lee, & Tzeng, 2009; Lee, et al., 2005). As for semantic radicals, Chen and Weekes (2004) showed that, three factors of the semantic radicals—*transparency,*[4] *consistency*[5] and *combinability*—affected sinogram recognition in both lexical decision (see also Feldman & Siok, 1999) and semantic categorization tasks.

Another line of research has shed light on semantic and phonological processing of the phonetic radicals which themselves are free standing sinograms. In a primed naming paradigm, at the SOA of 100 ms, the low-frequency irregular compound primes facilitated naming of targets which were homophonic with the phonetic radicals embedded in the primes, but the high-frequency irregular compound primes

[2] *Consistency* of a phonetic radical reflects the degree to which the pronunciation of a sinogram agrees with those of its orthographic neighbors containing the same phonetic radical.

[3] *Combinability* refers to the number of sinograms that contain the same radical.

[4] *Transparency* indicates the extent to which the meaning of the sinogram shares the same or similar meaning as its semantic radical.

[5] *Consistency* of a semantic radical refers to the ratio of the number of semantically transparent sinograms relative to the combinability of their semantic radicals.

did not (Zhou & Marslen-Wilson, 1999b). The follow-up experiments with only low-frequency compound primes examined the semantic processing of phonetic radicals, and showed facilitatory priming effects for targets which were semantically related to the phonetic radicals embedded in the primes at SOAs of both 57 and 100 ms (Zhou & Marslen-Wilson, 1999a). It was argued that sub-lexical phonological and semantic information of phonetic radicals embedded in low-frequency sinograms were activated and the frequency of sinograms modulated the activation process of phonetic radicals. Moreover, by tracking the N400 component in semantic priming experiments, an event-related potential (ERP) study found that the sub-lexical semantic information of the phonetic radicals embedded in regular sinograms was better preserved than those embedded in irregular sinograms during the first 50–100 ms of perceiving the sinograms (Lee, et al., 2006b).

Research on semantic and phonological processing of semantic radicals in sinogram recognition is limited in comparison to relevant research on phonetic radicals, and the available findings are indirect and possibly confound with the orthographic processing. In previous primed experiments, two types of orthographically similar (R+) primes which shared the same semantic radicals as the semantically transparent targets were recruited: the R+S+ primes were all semantically transparent sinograms, and thus as a whole they were also semantically related (S+) to the targets; the R+S− primes were all semantically opaque sinograms, and thus as a whole they were not semantically related (S−) to the targets. Priming effects of semantic similarity and orthographic similarity were then examined. Using primed lexical decision tasks, Feldman and Siok (1999) showed that both R+S+ and R+S− primes had facilitatory effects at the short SOA of 43 ms. However, at the SOA of 243 ms, the R+S− showed significant inhibitory effect whereas the facilitatory effects of the R+S+ primes remained. Crucially, in comparison to the semantically related (R−S+) primes, the R+S+ primes showed extra facilitatory effects at the SOA of 43 ms. Moreover, another kind of visually similar primes facilitated target identification at the SOA of 43 ms but have no effect at the SOA of 243 ms. Therefore the above extra facilitatory effects of R+S+ primes at the SOA of 43 ms and the inhibitory effects of R+S− primes at the SOA of 243 ms were interpreted to indicate the semantic processing of the semantic radicals embedded in primes. However, Zhou and Marslen-Wilson (1999b) did not find such extra facilitatory effects of R+S+ primes using the same paradigm. So these results were not consistent enough to demonstrate the semantic processing of semantic radicals, particularly at short SOAs. Furthermore, in the previous studies focusing on semantic radicals, the effects of the frequency of compound sinograms were not examined, or the phonetic radicals between related and control primes were not manipulated.

The current study

The current study focused on sub-lexical processing of semantic radicals which are themselves free standing sinograms. Given that processing of phonetic radicals which can be free standing sinograms was both phonological and semantic events

(Zhou & Marslen-Wilson, 1999a, b), as Taft's model predicted, processing of this kind of semantic radicals should be the same. Because in Taft's model, the representations of radicals do not differentiate the function of the radicals, findings regarding phonetic radicals is likely to be generalized to semantic radicals. In other words, when the semantic radicals are themselves free standing sinograms, their phonologies and semantics would be activated in visual word recognition at short SOAs, and the activation processes could also be modulated by the frequency of compound sinograms. Then a further natural extension for the current study was to manipulate the frequency of compound sinograms. Moreover, in terms of the generic model, any orthographic units of Chinese morphemes (including the whole sinogram, the embedded semantic and phonetic radicals) are activated in parallel. So the semantic radicals would be activated in parallel with the whole sinograms and the phonetic radicals. Then the relative frequency of these orthographic units should play a critical role in these parallel processes.

The current study followed the study of Zhou and Marslen-Wilson (1999a, b) and used the same primed naming paradigm to probe unequivocally into both semantic and phonological processing of semantic radicals. Thus semantic radicals which themselves are free standing sinograms were used in the current study. Moreover, all targets and primes have no orthographic similarity, thus avoiding the effects of orthographic similarity. Due to the functional nature of semantic radicals, Experiment 1 investigated the semantic processing of semantic radicals. In parallel with the first experiment of Zhou and Marslen-Wilson (1999b), both high- and low-frequency compound sinograms were used in Experiment 1 and the SOA was set at 100 ms. In the second experiment of Zhou and Marslen-Wilson (1999b), only low-frequency compound sinograms were used and semantic facilitatory effects of phonetic radicals were found at SOAs of 57 and 100 ms. Also, in our pilot tests of Experiment 1, only low-frequency primes showed effects. Therefore, Experiment 2 used only low-frequency compound sinograms as compound primes to examine the phonological processing of semantic radicals. Moreover, provided that sub-lexical processing of phonetic radicals showed facilitatory effects at SOAs of 57 and 100 ms, our prediction is that the priming effects from sub-lexical processing of semantic radicals at these two SOAs would not differ. To further examine the priming patterns at such short SOAs, the same two SOAs (i.e., 57 and 100 ms) were recruited in our Experiment 2. If the priming effects at these two SOAs are consistent, then it provides further evidence for the predictions from the aforementioned two models. In contrary, if the priming effects show different patterns at these SOAs, then the sub-lexical processing of semantic radicals and phonetic radicals are qualitatively different at these two SOAs.

Specifically, in Experiment 1, semantically opaque phonograms were used as primes, and targets were only semantically related to the semantic radicals embedded in the primes, but not to the primes themselves. In Experiment 2, targets were homophones of the semantic radicals embedded in the primes, but not of the primes themselves. To avoid effects of sub-lexical processing of phonetic radicals, all control primes were further manipulated to share the same phonetic radicals and regularity as the related primes. Therefore, any priming effect could be treated as direct evidences for the activated semantic and phonological information of the semantic radicals. The aims of this study were to explore (1) whether or not the semantic and phonological information of the semantic radicals are activated in sinogram recognition; (2) whether or not the activation processes of semantic radicals are affected by the lexical statistical characteristics, such as the frequency of the sinograms; and (3) whether or not the activation processes of semantic radicals are affected by the SOAs (i.e., 57 vs. 100 ms).

Method

Participants

Thirty-six right-handed subjects (18 female and 18 male, aged 19–25 years, mean 22.03 years), all native Mandarin speakers who grew up in Mainland China, participated in these experiments. All participants were undergraduate or graduate students from The Chinese University of Hong Kong at the time of the experiments. They had either normal or corrected-to-normal vision. Participants were paid for their participation and were allowed to quit any time during the experiments. Informed written consent was obtained from each participant. Approval to conduct the experiments was obtained from the Survey and Behavioral Research Ethics Committee of The Chinese University of Hong Kong.

All 36 participants took part in Experiment 1, and 30 out of the 36 participants also took part in Experiment 2.

Procedure

Participants were seated about 50 cm from the screen. In Experiment 1, each participant was presented 20 practice prime–target trials followed by 208 test trials in random order during 8 test blocks (each block additionally included two filler trials). After Experiment 1, 30 participants also attended Experiment 2, in which each participant was given 104 experimental trials and 64 filler trials in random order during 8 test blocks. Participants could take a break between test blocks. The first two trials after each break were always filler trials, and all filler trials were excluded from analysis. In each trial, a fixation sign, "+", was first presented at the center of the screen for 300 ms. A prime was then presented for 100 ms (SOA 100) in Experiment 1 and for either 100 ms (SOA 100) or 57 ms (SOA 57) in Experiment 2, and was subsequently overwritten immediately by the corresponding target, which was presented for 400 ms. The target was followed by a blank, which was displayed until participants named the target. Participants were instructed to name the target as accurately and quickly as possible. The inter-trial interval was 3 s. Both accuracy and reaction time (RT) with reference to the onset time of target presentation were recorded. It took around 40 min to complete both experiments.

RT was measured through a voice key trigger in a PST serial response box (Psychology Software Tools, Inc.) and all experiments were controlled by the software E-Prime 2.0 (Psychology Software Tools, Inc.).

Experiment 1: semantic primed naming

Experiment 1 had two aims. The primary aim was to examine whether the semantic information of embedded semantic radicals was activated in sinogram recognition. The secondary aim was to examine whether this activation process was modulated by the frequency of the host sinograms.

Materials

As shown in Appendix Tables 3 and 4, the stimuli consisted of 48 pairs of phonograms that were used as primes and had a left–right structure in simplified Chinese. Each pair shared the same phonetic radical, regularity and structure. Phonograms were chosen from a word frequency statistics database from Centre for Chinese Linguistics at Peking University (http://ccl.pku.edu.cn:8080/ccl_corpus/CCL_CC_Sta_Xiandai.pdf). 24 pairs of stimuli were high-frequency sinograms (all above 29 per million, Mean = 245 per million and SD = 256), while the other 24 pairs of stimuli were low-frequency sinograms (all below 14 per million, Mean = 4.5 per million and SD = 3.8). There was no significant difference between each pair in terms of sinogram frequency ($t(23) = 0.504$, $p = 0.619$ for the 24 high-frequency pairs, $t(23) = 0.455$, $p = 0.653$ for the 24 low-frequency pairs), or number of strokes ($t(23) = -1.192$, $p = 0.245$ for the 24 high-frequency pairs, $t(23) = -1.961$, $p = 0.062$ for the 24 low-frequency pairs).

To differentiate the meanings between the primes and their semantic radicals, semantically opaque[6] phonograms were selected as primes. A pretest about the semantic transparency of primes was conducted with 10 participants (5 female and 5 male, aged from 21 to 25 years, exclusive from participants in naming experiments) who were all native Mandarin speakers. Participants rated the semantic transparency of each prime phonogram on a 5-point scale questionnaire,[7] ranging from 1 (not related at all) to 5 (extremely related). Semantically opaque sinograms (low value) were selected as prime stimuli in the related condition so that meanings of the semantic radicals differed from those of the primes themselves. The average transparency value for low-frequency primes in the related condition was 1.86 and that for high-frequency primes in the related condition was 1.66.

To ensure the semantic relatedness between related primes and targets, another 10 native Mandarin speaking participants (5 male and 5 female, also exclusive from participants in naming experiments) rated the semantic relatedness between the embedded semantic radicals and the targets on a 7-point scale questionnaire,[8] ranging from 1 (not related at all) to 7 (highly semantically related). Sinograms rated as highly semantically related with the selected semantic radicals were chosen as targets in Experiment 1. For each pair of primes, two sinograms were chosen as

[6] The semantic radical itself has a distinct meaning from that of the host sinograms.

[7] The rating questionnaire consisted of 309 sinograms involving both transparent and opaque sinograms.

[8] The questionnaire included 202 sinogram pairs with both highly semantically related and unrelated pairs.

their targets to increase the number of experimental trials. The average semantic relatedness score of high-frequency related primes was 4.65 and that of low-frequency related primes was 4.88. Because all critical comparisons in our Experiment 1 were within-target (as detailed in the experimental design), the target frequency was not manipulated. However, the difference between the target frequency (Mean = 365 per million, SD = 436) for high-frequency primes and that (Mean = 489 per million, SD = 886) for low-frequency primes were insignificant, $t(94) = -0.868$, $p = 0.388$. Also, in terms of number of strokes, there was no significant difference between targets for high-frequency primes and those for low-frequency primes, $t(94) = -1.325$, $p = 0.189$.

Therefore, forty-eight pairs of primes were matched with 96 different targets. In other words, each target was paired with a pair of primes. A total of 192 prime–target pairs were used for two types of priming condition (i.e., 96 pairs for each of the high and low-frequency prime conditions). Furthermore half of the primes (24 pairs) were regular phonograms (equally distributed in the high and low-frequency pairs), and half were irregular phonograms (also equally distributed).

Experimental design

There were two within-subject variables: Prime frequency (HIGH vs. LOW), and relatedness (RELATED vs. CONTROL). In the RELATED condition, the prime was a semantically opaque phonogram and the target was only semantically related to the meaning of the semantic radical embedded in the prime. However, the target had no association with the prime or its embedded phonetic radical in terms of orthography, phonology or semantics. In the CONTROL condition, the prime, which shared the same phonetic radical and regularity as the prime in the RELATED condition, was not orthographically, phonologically, or semantically related to the target sinogram at either the lexical or sub-lexical level (see Table 1).

The CONTROL condition served as the baseline. The primes of the CONTROL condition were matched with those of the RELATED condition in terms of frequency, visual complexity and regularity, and they were paired with the same two targets. All critical comparisons were performed within-target, avoiding the

Table 1 Sample stimuli of primes and targets in experiment 1

	Priming condition	RELATED	CONTROL	Target 1	Target 2
Lexical level	Phonogram (irregular)	弥 (mi2: full)	称 (cheng4: match)	箭 (jian4: **arrow**)	剑 (jian4: **sword**)
Sub-lexical level	Semantic radical	弓 (gong1: **bow**)	禾 (he2: grain)		
Sub-lexical level	Phonetic radical	尔 (er3: you)			

difficulties in matching targets on many possible parameters that could influence the naming performance.

In order to balance the repetition effect, a Latin square design was applied to eight blocks to make sure that the same target was not repeated within each block and targets paired with four types of primes were in equal number in each block. For each participant the sequence of blocks was randomized, as was the order of presentation of prime–target pairs in each block. By doing so, the repetition effect of targets was balanced across experimental conditions.

Results of Experiment 1

Data of one left-handed female subject and two male subjects with outlier RT (outside of 2 SDs from the population mean RT) were rejected from analysis. Two-way repeated-measures analysis of variance (ANOVA) was carried out for RTs by participants (F_1) and by items (F_2). In item analyses, the prime frequency was treated as a between-item variable and the relatedness was treated as a within-item variable.

In the naming task, all participants obtained accuracy rates above 90 %, with mean accuracy of 96 %. For each participant, any targets with RT outside of 2 SDs from the individual mean were excluded from analysis.

The main test showed significant main effects of prime frequency only in participant analysis. Compared with targets preceded by low-frequency primes, those preceded by high-frequency primes were named significantly faster (+7 ms) by participant, $F_1(1, 32) = 13.541$, $p < 0.05$, MSE = 82, $\eta_p^2 = 0.297$, but not significant by item, $F_2(1, 94) = 1.672$, $p = 0.199$, MSE = 1619.711, $\eta_p^2 = 0.017$. There was a significant two-way interaction between prime frequency and relatedness, $F_1(1, 32) = 10.118$, $p < 0.05$, MSE = 30.033, $\eta_p^2 = 0.240$; $F_2(1, 94) = 3.967$, $p < 0.05$, MSE = 105.62, $\eta_p^2 = 0.040$. Then simple main effect analyses of the RELATEDNESS were conducted with Bonferroni adjustment. For low-frequency primes, the RELATED primes had a significant facilitatory effect (+5 ms) on naming targets compared with CONTROL primes, $F_1(1, 32) = 4.830$, $p < 0.05$, $\eta_p^2 = 0.131$; $F_2(1, 94) = 3.989$, $p < 0.05$, $\eta_p^2 = 0.041$ (see Fig. 2). In contrast, for high-frequency primes, no effect was observed, $F_1(1, 32) = 2.592$, $p = 0.117$, $\eta_p^2 = 0.075$; $F_2(1, 94) = 0.672$, $p = 0.415$, $\eta_p^2 = 0.007$.

Discussion

Since the related prime as a whole has no association with the target and only the embedded semantic radical is semantically related to targets, the observed priming effects could only be attributed to the activation of meanings of the semantic radicals embedded in primes. The sub-lexical semantic facilitatory priming effect observed in Experiment 1 demonstrates that the semantic information of semantic radicals embedded in low-frequency phonogram primes is activated. Their activation spreads to the semantically related target sinograms, resulting in a significantly faster naming speed for the RELATED condition in comparison to the

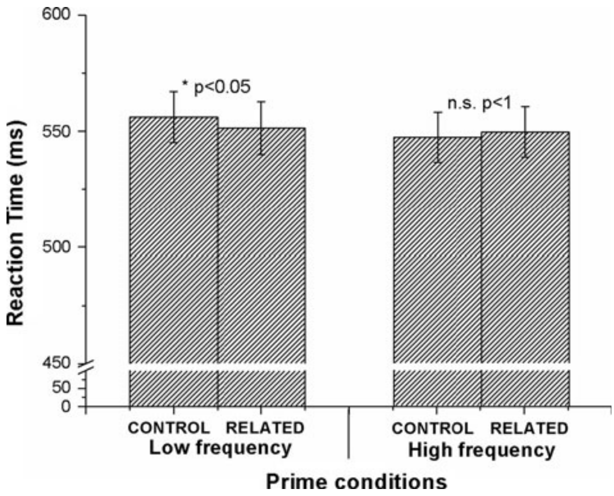

Fig. 2 Results of the semantic primed naming experiment (The *bars* represent standard errors)

CONTROL condition. In contrast, the absence of facilitatory priming effects in high-frequency RELATED primes indicates weaker or no semantic activation of semantic radicals embedded in high-frequency phonogram primes. In other words, the frequency of phonograms modulates the effects of sub-lexical processing of the embedded semantic radicals.

The main effect of prime frequency was likely due to the uncontrolled statistical properties of targets for high- and low-frequency primes. However, the critical comparisons in our experiment were within targets: The same targets were paired with RELATED and CONTROL primes. Therefore, it is unlikely that the statistical properties of targets affected our results on relatedness.

Equally important, regarding the different patterns observed in high- and low-frequency primes, there is a possibility that the semantic radicals embedded in low-frequency primes are more frequently used as simple sinograms than those embedded in high-frequency primes, since previous literature has shown that the frequency of simple sinograms affects the processing of the host compound sinograms which contain them as radicals: In lexical decision tasks, it was found that the higher the token frequency of the former, the faster the identification of the latter (Taft et al., 2000). Moreover, in primed lexical decision tasks, the pre-exposure of a sinogram that is also a constituent radical of another sinogram facilitated the recognition of the latter (Ding et al., 2004). Therefore, we carried out further analyses on the lexical frequency of semantic radicals (i.e., the token frequency of the corresponding simple sinograms) embedded in high- and low-frequency primes. Post hoc independent t test of lexical frequency of semantic radicals between high- and low-frequency primes shows that, there is no difference on the lexical frequency of semantic radicals between two groups of radicals, $t(46) = 1.143$, $p = 0.358$. So the possible role of lexical frequency of semantic radicals between high- and low-frequency primes is ruled out.

Focusing on semantic radicals, the results of Experiment 1 are consistent with the previous study on sub-lexical semantic processing of phonetic radicals embedded in low-frequency sinograms (Zhou & Marslen-Wilson, 1999a). The frequency effect in our Experiment 1 is also consistent with that of phonological processing of phonetic radicals (Zhou & Marslen-Wilson, 1999b). It has been well established that the sub-lexical phonological processing of phonetic radicals interacts with the frequency of the host compound sinograms which contain these radicals (e.g., Hue, 1992). For instance, regular compound sinograms are found to be named faster than the irregular compound sinograms and this regularity effect is observed only in low-frequency compound sinograms, but not in high-frequency compound sinograms (Seidenberg, 1985). However, the question of whether the frequency effect is applicable to the sub-lexical processing of semantic radicals is not addressed (e.g., Feldman & Siok, 1999; Zhou & Marslen-Wilson, 1999b). Our results suggest that the sub-lexical semantic processing of semantic radicals interacts with the frequency of the host compound sinograms which contain these semantic radicals.

This interaction, together with that in the processing of phonetic radicals, can be easily explained by the relative time course of orthographic processing and phonological/semantic processing based on interaction-activation principles (e.g., Seidenberg, 1985). According to this principle, orthographic processing of high-frequency sinograms is sufficiently fast to allow word recognition before phonological and semantic processing of their components, that is, radicals and strokes. However, the processing of low-frequency words is inefficient, so the phonological or semantic activation of their components has time to accrue to influence word recognition. Alternatively, it might be that: The semantic radicals embedded in high-frequency sinograms are less activated than embedded in low-frequency sinograms; or the stronger activation of high-frequency primes as a whole suppresses the activation of semantic radicals. Therefore the sub-lexical processing of semantic radicals embedded in high-frequency primes is absent in this behavioral study.

Experiment 2: phonological primed naming

The second experiment was carried out to investigate whether or not the phonological information of the semantic radicals embedded in sinograms was activated and whether this sub-lexical activation differed at the SOAs of 57 and 100 ms.

Materials

As shown in Appendix Table 5, the materials consisted of 26 sets of primes and each set of primes contained four kinds of prime condition as detailed in the Experimental design below. Since our pilot results of Experiment 1 only showed facilitatory sub-lexical effects for low-frequency primes, in Experiment 2 we recruited low-frequency phonograms as sub-lexical related primes (All below

14 per million, Mean = 3.4 per million, SD = 3.2). The Experiment 2 focused on the phonological processing of semantic radicals, so the semantic transparency of primes was not manipulated.

Each set of primes was paired with one target. All comparisons were within-target, so the frequency of targets was not manipulated, Mean = 367.7 per million, SD = 744.6. Thus a total of 104 prime–target pairs were used in Experiment 2. Meanwhile another 64 prime–target pairs were used as fillers. All primes and targets were chosen from the same database as used in Experiment 1.

Experimental design

According to two within-subject factors, RELATEDNESS (related vs. control) and TYPE (sub-lexical vs. lexical), Experiment 2 consisted of four kinds of prime condition: (1) The sub-lexical phonologically related prime condition (SR), in which the prime itself was not semantically, phonologically or orthographically related to the target and the target was only a homophone of the embedded semantic radical. (2) The sub-lexical control condition (SC), in which the prime here and the prime in the SR condition shared the same phonetic radical and regularity, and matched in terms of frequency and visual complexity, but had no association with the target. There was no significant difference between the SR and SC condition in terms of frequency, $t(26) = 1.592$, $p = 0.118$. (3) The lexical homophone condition (LR), where the prime was the semantic radical embedded in the prime in the SR condition and therefore the prime itself was a homophone of the target. The mean frequency of primes in the SR conditions was 373.2 per million (SD = 564.5). (4) The lexical control condition (LC), where the prime was matched with the prime in the LR condition in terms of visual complexity and frequency, and the prime itself had no relation with the target in terms of semantics, phonology and orthography (see Table 2). There was no significant difference between the LR and SR condition in terms of frequency, $t(26) = -0.052$, $p = 0.959$. This experiment also contained one between-subject factor: SOA (57 ms vs. 100 ms). Specifically, 15 subjects (7F, mean age = 22.35) attended the condition of SOA of 57 ms, while another 15 subjects (7F, mean age = 21.87) attended the condition of SOA of 100 ms.

Table 2 Sample stimuli of primes and targets in experiment 2

Priming type	Sub-lexical		Lexical		Target
Relatedness	Related (SR)	Control (SC)	Related (LR)	Control (LC)	
	贻 (yi2: present)	殆 (dai4: dangerous)	贝 (bei4: shell)	厅 (ting11: hall)	辈 (**bei4**: generation)
The semantic radicals	贝 (**bei4**: shell)	歹 (dai3: evil)			
The phonetic radical	台 (tai2: tower) (Shared phonetic)				

In order to balance the repetition effect, a Latin square design was applied to 8 blocks such that, in each block, there were equal numbers of targets from the four prime conditions and there was no repetition of the same target within each block. For each participant the sequence of blocks was randomized and prime-target pairs were also randomized in each block. By doing so, the repetition effect of targets was balanced across experimental conditions.

Results in experiment 2

Data of one male subject for the condition of SOA 57 ms with outlier RT (outside of 2 SDs from the population mean RT) were rejected from analysis. On average, the participants responded correctly to 98 % of the sinogram naming task. Therefore, only RTs were analyzed in the results. For each participant, any targets with RT outside of 2 SDs from the individual's mean RT were excluded from the analysis. Three-way mixed design repeated-measures ANOVA was carried out for RTs with two within-subject factors, RELATEDNESS (related vs. control) and TYPE (lexical vs. sub-lexical), and one between-subject factor, SOA (57 vs. 100 ms). In analysis-by-item (F_2), all these variables were treated as within-item factors.

The main test showed significant main effects of all three variables: TYPE, RELATENESS and SOA. Compared with sub-lexical primes, lexical primes significantly facilitated target naming, F_1 (1, 27) = 10.480, $p < 0.05$, MSE = 202.761, $\eta_p^2 = 0.280$; $F_2(1, 25) = 6.029$, $p < 0.05$, MSE = 530.415, $\eta_p^2 = 0.194$. Also, related primes significantly facilitated target naming, $F_1(1, 27) = 72.108$, $p < 0.001$, MSE = 116.822, $\eta_p^2 = 0.728$; $F_2(1, 25) = 31.878$, $p < 0.001$, MSE = 414.360, $\eta_p^2 = 0.560$. Moreover, compared with participants at the SOA of 100 ms, participants at the SOA of 57 ms named targets significantly faster, $F_1(1, 27) = 5.295$, $p < 0.05$, MSE = 18170.929, $\eta_p^2 = 0.164$; $F_2(1, 25) = 164.007$, $p < 0.001$, MSE = 925.913, $\eta_p^2 = 0.868$. There was a significant interaction between TYPE and RELATENESS, $F_1(1, 27) = 23.906$, $p < 0.001$, MSE = 130.846, $\eta_p^2 = 0.470$; $F_2(1, 25) = 12.291$, $p < 0.05$, MSE = 605.223, $\eta_p^2 = 0.330$. No other significant interaction effects were observed.

Simple main effect analyses of the RELATEDNESS were conducted with Bonferroni adjustment. For lexical priming condition, the difference in RT (+27 ms) between LR and LC was significant, $F_1(1, 27) = 80.231$, $p < 0.001$, $\eta_p^2 = 0.748$; $F_2(1, 25) = 33.145$, $p < 0.001$, $\eta_p^2 = 0.570$. Regarding the sub-lexical condition, the difference in RT (+7 ms) between SR and SC was also significant by participant, $F_1(1, 28) = 5.754$, $p < 0.05$, $\eta_p^2 = 0.176$, but not significant by item, $F_2(1, 25) = 1.006$, $p = 0.326$, $\eta_p^2 = 0.039$. The significant difference indicated that related primes facilitated target naming (see Fig. 3). In both lexical and sub-lexical conditions, the interaction between SOA and RELATEDNESS was insignificant, suggesting that there was no substantial differences in the effects of relatedness between the two SOAs.

Discussion

The phonological facilitatory effect of the LR condition demonstrates the phonological activation of primes lexically and the facilitatory effect of lexical

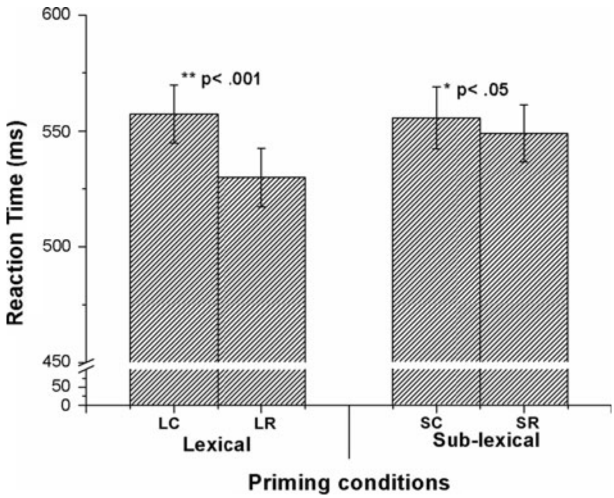

Fig. 3 Results of the phonological primed naming experiment (The *bars* represent standard errors)

homophones. Moreover, since the only association between primes in the SR condition and targets was in phonology, the priming effects observed in that condition could only be attributed to the activation of phonological information of the semantic radicals embedded in primes. The phonological facilitatory effect of the SR condition demonstrates the activation of phonological information of the semantic radicals embedded in low-frequency phonograms: Targets which are homophones of the semantic radicals embedded in priming phonograms share the same phonological representations as the semantic radicals, so the activation of phonological representations of the semantic radicals facilitates the naming of targets.

Compared with the strong lexical phonological facilitatory effects (+27 ms) of the LR condition, the relatively small facilitatory effects (+7 ms) and the insignificant result in item analyses of the SR condition suggest that the sub-lexical phonological processing of semantic radicals is much weaker than their corresponding lexical processing when they stand alone as simple sinograms.

The main effect of the between-subject variable SOA may be due to individual differences from these two groups of participants. Then group differences were examined in terms of their RT in the Experiment 1. Independent *t* test of the mean RT in Experiment 1 was conducted between the participants who participated the condition of SOA 57 ms of Experiment 2 and those who participated the condition of SOA 100 ms of Experiment 2. The results show that, participants who attended the condition of SOA 57 ms of Experiment 2 named sinograms significantly faster than those attended the condition of SOA 100 ms of Experiment 2, $t(46) = -2.106$, $p < 0.05$. This confirms that the main effects of SOA result from group differences in participants. The insignificant interaction between SOA and relatedness in lexical condition is consistent with previous studies (e.g., Perfetti & Tan, 1998) which found facilitatory effects of lexical homophones at SOAs of 57 and 100 ms. Equally important, the non-significant interaction between SOA and relatedness in the sub-lexical condition confirms our predictions that there is no substantial difference for the sub-lexical processing of semantic radicals between the two SOAs.

Concerning phonological activation of sinograms at both the lexical and sub-lexical levels, previous studies only considered the phonology of sinograms and that of the embedded phonetic radicals (Yang, Peng, Charles, & Tan, 2000; Zhou & Marslen-Wilson, 1999b). Our study has proved the existence of phonological activation of the embedded semantic radicals at the sub-lexical level. Therefore, for some sinograms, there is competition among the pronunciations of the sinogram itself, of its embedded phonetic and semantic radicals (if all of them have pronunciations on their own). However, how the competition between the lexical and sub-lexical phonological information is resolved during sinogram recognition needs further investigation.

General discussion

The main purpose of this study was to examine the sub-lexical semantic and phonological processing of semantic radicals which were themselves free standing sinograms using a primed naming paradigm. Experiment 1 demonstrates that, at an SOA of 100 ms, the meaning of this kind of semantic radicals is activated when they are embedded in low-frequency phonograms, but weakly or not when they are embedded in high-frequency phonograms. The results of Experiment 1 provide further evidence that sinogram frequency modulates the sub-lexical activation process of radicals embedded in sinograms. Experiment 2 demonstrates that the phonological information of this kind of semantic radical embedded in low-frequency phonograms is also activated, and no substantial difference in phonological activation was observed between SOAs of 57 and 100 ms.

These results can be easily accommodated in Taft's model: Radicals which can also be free standing sinograms have both a sinogram representation at the lexical level and a radical representation at the sub-lexical level. Activation of such radical representations is mediated by their corresponding sinogram representations which link to their phonological and semantic information via lemma units (see also Fig. 1). This point explains why semantic radicals when embedded in low-frequency sinograms have facilitatory effects in both semantic and phonological priming paradigms.

Furthermore, the interaction effects between prime lexical frequency and relatedness in Experiment 1 and the superior priming effects of lexical representations in Experiment 2 can be explained in Taft's hierarchical model. According to this model, the activation of semantic and phonological information of the semantic radicals is a byproduct of activation of the radical representations (see also Fig. 1). Possibly, regarding semantic radicals embedded in high-frequency sinograms, activation of radical representations is not strong or suppressed by the activation of lexical representations of their host sinograms which contain these radicals. In other words, the activation of lexical representation of high-frequency sinograms may involve more top-down processing from lexical to sub-lexical level, so the indirect link between radical representations and their corresponding semantic and phonological information is absent or transient. Moreover, the more direct link (still via Lemma) between the lexical representations and their corresponding phonological and semantic representations, can explain the stronger priming effects of the LR condition in Experiment 2; the indirect link between radical representations and their corresponding phonological and semantic representations, can further explain the weaker phonological priming effects of the SR condition in Experiment 2.

Equally important, our current findings of semantic radicals are in agreement with predictions of Taft's hierarchical model which does not emphasize the function of radicals in the orthographic system (Taft, 2006; Taft, et al., 2000). According to this model, the orthographic representation of radicals differentiates the position of radicals in complex sinograms, but not the function of radicals. Then any effects from sub-lexical processing of phonetic radicals could be applied to that of semantic radicals. Our experiments confirm the predictions that the sub-lexical semantic and phonological processing of semantic radicals has quantitatively the same effects as that of phonetic radicals (Zhou & Marslen-Wilson, 1999b). The function of radicals might contribute to the position sensitive orthographic representations of radicals, since most compound sinograms are SP sinograms. However, this assumption is beyond the aims of our study and needs further explorations. In summary, radicals are processed sub-lexically in the same way irrespective of their functions.

More importantly, we noticed that some radicals which cannot be free standing sinograms, have only semantic information (e.g., the radical 扌, referring to hand-related meaning) or only phonological information (e.g., the phonetic radical 鬲, ge2, bearing no meanings). The knowledge of these radicals is acquired by native Chinese readers since childhood (Ho, Ng, & Ng, 2003; Shu & Anderson, 1997). However, Taft's model has not addressed how radicals which themselves are not legal sinograms link to the semantic or phonological representations. So for this kind of radicals, it might be that the awareness of radicals' function helps to establish linkages between these orthographic representations and their corresponding phonological or semantic representations in the mental lexicon. However, this assumption also needs further investigations.

On the other hand, our results are also consistent with the generic model in which radicals and sinograms are represented at the same level and are activated in parallel. According to this model, the pronunciations and meanings of radicals and host sinograms are activated in parallel, and then the lexical frequency of these orthographic units plays an important role. Specifically, in our study, as for semantic and phonological processing of radicals, the lexical frequency of radicals is crucial for predicting the results. Therefore, post hoc paired *t* tests were carried out between frequency of primes and the lexical frequency of the embedded semantic radicals in both high- and low-frequency stimuli. For high-frequency primes, the frequency of primes are marginally higher than the lexical frequency of their semantic radicals, $t(1,23) = 1.852$, $p = 0.077$. For low-frequency primes, the frequency of primes are significantly lower than the lexical frequency of their semantic radicals, $t(1,23) = 5.110$, $p < 0.001$. Then it appears reasonable to infer that activation of high-frequency primes as a whole is faster and stronger than that of their embedded semantic radicals, and that activation of low-frequency primes as a whole lags behind that of their embedded semantic radicals. In terms of this account, it would be interesting to see whether there will be any facilitatory effects in medium-frequency sinograms where the frequency of radicals is equal with that of the host sinograms.

In summary, our results suggest that a radical, whether it is a semantic or phonetic radical, has a unique representation in the mental lexicon, and the processing of a radical could be both semantic and phonological events. However, besides these radicals which have their own pronunciations and meanings, there are also many semantic radicals with no pronunciations, and phonetic radical with no meanings. So one further question in Chinese sinogram recognition of how such kind of radicals are processed and represented in the mental lexicon needs further exploration.

Conclusion

By using a primed naming paradigm, the current study examined the activation processes of semantic radicals embedded in phonograms when these radicals themselves are free standing sinograms. Our results demonstrate that both the semantic and phonological information of such radicals embedded in low-frequency sinograms are activated. Furthermore, these activation processes are modulated by the lexical frequency of the host phonograms. The present study shows that sub-lexical processing of semantic radicals is similar to that of phonetic radicals embedded in sinograms (Lee, et al., 2006b; Zhou & Marslen-Wilson, 1999a, b), indicating no fundamental difference in processing this kind of phonetic and semantic radicals for short SOAs. These results support the view that a radical has a unique representation irrespective of its function in the hierarchical orthographic system of Taft’s model for sinogram recognition.

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Appendix

See Tables 3, 4 and 5.

Table 3 Stimuli of high-frequency in semantic primed naming experiment (Primes of the first 12 pairs are irregular sinograms, and the remaining 12 pairs are regular sinograms)

Item no	Prime type		Semantic radical	Target	
	Related	Control		Target 1	Target 2
1	坏	杯	土	沙	葬
2	始	抬	女	儿	男
3	嫌	赚	女	郎	淑
4	稳	隐	禾	米	饭
5	杭	航	木	丛	叶
6	般	股	舟	载	车
7	静	净	青	蓝	黄
8	默	状	黑	绿	暗
9	叙	斜	又	再	且
10	骗	偏	马	虎	鞍
11	弥	称	弓	箭	剑
12	斜	叙	斗	战	打
13	极	级	木	筏	花
14	欺	期	欠	缺	债
15	玛	码	王	臣	侯
16	稿	搞	禾	田	植
17	辅	铺	车	舟	马
18	预	豫	页	书	张
19	增	赠	土	灰	水
20	胜	牲	月	圆	光
21	校	较	木	炭	石
22	职	织	耳	鸣	鼻
23	较	校	车	骑	路
24	领	邻	页	册	面

Table 4 Stimuli of low-frequency in semantic primed naming experiment (Primes of the first 12 pairs are irregular sinograms, and the remaining 12 pairs are regular sinograms)

Item no	Prime type		Semantic radical	Target	
	Related	Control		Target 1	Target 2
1	脍	侩	月	皎	亮
2	肮	吭	月	星	弯
3	畸	犄	田	耕	农
4	秤	抨	禾	苗	草
5	稚	帷	禾	谷	麦
6	耽	枕	耳	脸	听
7	毓	梳	每	各	常
8	韶	貂	音	响	乐

Table 4 continued

Item no	Prime type		Semantic radical	Target	
	Related	Control		Target 1	Target 2
9	黩	椟	黑	影	紫
10	贻	殆	贝	壳	珠
11	赅	垓	贝	海	螺
12	轶	佚	车	船	驾
13	墉	慵	土	金	泥
14	娓	艉	女	孩	子
15	皖	烷	白	纯	昼
16	膳	缮	月	饼	季
17	瑾	槿	王	法	冠
18	琉	硫	王	君	将
19	珈	枷	王	贼	霸
20	腥	猩	月	年	夜
21	矜	衿	矛	盾	刺
22	黜	绌	黑	乌	暗
23	颀	鸬	页	篇	纸
24	骇	骸	马	牛	鹿

Table 5 Stimuli of low-frequency in Experiment 2

Item no	Prime type				Target
	Sub-lexical related	Sub-lexical control	Lexical related	Lexical control	
1	肮	吭	月	天	悦
2	秤	抨	禾	从	何
3	贻	殆	贝	厅	辈
4	楷	偕	木	升	幕
5	觚	弧	角	夜	脚
6	弧	觚	弓	丫	功
7	韫	媪	韦	匹	尾
8	牍	犊	片	友	骗
9	韶	貂	音	念	阴
10	帖	拈	巾	冈	金
11	龌	幄	齿	畏	耻
12	舵	驼	舟	吾	粥
13	蝎	碣	虫	尖	崇
14	畸	犄	田	句	甜
15	鞠	掬	革	非	隔
16	颀	鸬	页	灰	叶
17	矜	衿	矛	乏	毛
18	硫	琉	石	未	时

Table 5 continued

Item no	Prime type				Target
	Sub-lexical related	Sub-lexical control	Lexical related	Lexical control	
19	峥	狰	山	车	删
20	斓	澜	文	公	闻
21	舭	娓	舟	勾	周
22	翎	瓴	羽	旱	宇
23	聆	羚	耳	鱼	尔
24	髅	镂	骨	唐	谷
25	睫	婕	目	华	牧
26	麒	骐	鹿	翁	露

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