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Sublexical Processing in Reading Chinese: A Development Study

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Three primed naming experiments were conducted to investigate the development of sublexical processing in reading Chinese. Target characters were either homophonic to (Experiments 1 and 2) or semantically related to (Experiment 3) phonetic radicals embedded in irregular complex characters, but not to the complex character themselves. For both the third and sixth grade school children, targets were named faster when they were preceded by such complex characters than by unrelated primes, although the semantic effect of complex characters was not significant for the third grade children. It is argued that, from early on in learning to read Chinese, phonetic radicals embedded in complex characters are decomposed from visual input and used to activate their own phonological and semantic properties, in parallel to the processing of whole characters.

INTRODUCTION

Most complex Chinese characters are composed of a semantic radical and a phonetic radical (Li, 1993; Yin & Rohsenhow, 1994). While semantic radicals have the function of indicating the semantic category of

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morphemes corresponding to whole characters, phonetic radicals have the function of pointing to the pronunciations of whole characters. However, due to the evolution of the writing system, many such characters are no longer pronounced in the same way as their phonetic radicals. Previous studies (Hue, 1992; Peng, Yang, & Chen, 1994; Seidenberg, 1985) have found that the ''regularity'' of phonetic radicals in encoding phonological information for whole characters influences phonological processing of these characters, at least when they are of low frequency. Regular complex characters, which are pronounced in the same way as their phonetic radicals, are named faster than frequency-matched simple characters, which have no phonetic radicals, or irregular complex characters, which have different pronunciations from their phonetic radicals. These findings are often interpreted as suggesting that phonetic radicals embedded in complex characters are decomposed from visual input and mapped onto their own phonological representations as well as representations of other characters containing these radicals. The co-operative and competitive interaction between phonological processing of whole characters and their phonetic radicals leads to the ''regularity'' and ''consistency'' effect in naming complex characters (Seidenberg, 1985; Zhou & Marslen-Wilson, 1999a). Thus, sublexical processing of phonetic radicals in reading Chinese is thought as analogous to sublexical processing of letter strings in reading alphabetic words, whose function is to provide sources of phonological activation (and semantic activation) for whole words (Coltheart, Curtis, Atkins, & Haller, 1993; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). Some researchers (Cheng, 1992; Flores d'Arcais, Saito, & Kawakami, 1995), however, went so far to suggest that, because the phonetic radical-sound correspondences are over-learned in Chinese, they could be used in the same way as the grapheme-phoneme correspondences in alphabetic languages, presumably to compute ''pre-lexical'' phonology for whole characters.

The main purpose of this study was to investigate how school children, in learning to read complex Chinese characters, use phonological information provided by phonetic radicals and whether sublexical processing of phonetic radicals embedded in complex characters is restricted to phonology, involving only activation of phonological information associated with the phonetic radicals. Before presenting our experiments, we give a brief introduction to the structural properties of Chinese characters and previous research on sublexical processing of phonetic radicals.

THE STRUCTURE OF CHINESE CHARACTERS AND SUBLEXICAL PROCESSING OF PHONETIC RADICALS

The Chinese writing system is often described as logographic or morphosyllabic, where the basic orthographic units, the characters, correspond directly to morphemic meanings and syllables. With some exceptions, each character in isolation represents one morpheme and has one pronunciation, although different characters may have the same pronunciations. Modern Chinese characters can be broadly differentiated into two categories (Li, 1993); simple and complex,[1] both of which are composed of strokes and arranged in squares of similar size. Simple characters (e.g., 土 tu[3], *soil*, *earth*) make up about 5% of the total characters in Modern Chinese. They are holistic visual patterns that cannot be divided meaningfully into sublexical units. Complex characters constitute about 95% of all modern Chinese characters (Li, 1993; Yin & Rohsenow, 1994) and 87% of characters learned by Chinese school children (Shu, Wu, Zheng, & Zhou, 1998). Most of these characters are composed of a semantic radical on the left and a phonetic radical on the right (e.g., 城 cheng[2], *city*, in which the phonetic radical is 成 cheng[2], *become*),[2] although some arrange their radicals in other ways (see Yin & Rohsenow, 1994).

As far as the phonological relations between complex characters and their phonetic radicals are concerned, there are about one third of the complex characters ("regular" characters, e.g., 清 qing[1], *clear*, whose phonetic radical is 青 qing[1], *blue*) that have exactly the same pronunciations as their phonetic radicals (Fan, Gao, & Ao, 1984; Li & Kang, 1993). About one third of complex characters ("irregular" characters, 猜 cai[1], *guess*) bear no phonological relations with their phonetic radicals at all. The final one third share some aspect of their phonology, such as segmented rhyming parts (e.g., 精 jing[1], *essence*), or the initial consonants (e.g., 倩 qian[4], *pretty*) with their phonetic radicals. Most phonetic radicals can be involved in both regular and irregular characters. Unlike letter clusters or graphemes in alphabetic words,

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[1] Characters were differentiated into six categories (pictographic, indicative, associative, picto-phonetic, notative, and burrowed) in a classic work (Shuwen Jiezi, 121 A.D., see Yin & Rohsenow, 1994), which is still referred to today. While the first four categories were based on the way the characters were created, the last two refer to the expansion of the use of existing characters. It seems that there is little psychological relevance of many of these categories (e.g., pictograms or ideograms).

[2] Throughout this paper, the pronunciations of Chinese characters are given in *pinyin*, the alphabetic system used in mainland China. Numbers in brackets or parentheses represent the lexical tones of syllables.

phonetic radicals provide clues to the pronunciations of whole characters, rather than to a part of them. Moreover, most phonetic radicals (92%) can stand alone as meaningful characters, even though their meanings mostly have nothing to do with the meanings of whole characters.

From early on school children are exposed to different types of characters and different phonological relations between complex characters and their phonetic radicals. According to our analyses of characters learned by Chinese school children (Shu et al., 1998), the proportion of regular complex characters (disregarding the tonal differences between whole characters and their phonetic radicals) increases from 31% of all complex characters learned in the second grade to 41% in the sixth grade, while irregular characters (having segmental differences between complex characters and their phonetic radicals) increases from 40% in the second grade to about 46% in the sixth grade. Simple characters take about 45% and 29% respectively of all characters learned in the first and second grades. Among them, over 75% become phonetic radicals of complex characters learned in the later grades. Simple characters learned in school usually have higher frequency than complex characters that use them as phonetic radicals. The average frequency of phonetic radicals as independent characters is 730 per million in adult reading materials while the average frequency of complex characters containing these radicals is 15 per million. By the end of the third grade, children have learned about 2000 characters. By the end of the sixth grade, children have learned about 3260 characters, which are not far away from the 4570 characters covering most adult reading materials (Institute of Language Teaching and Research, 1986).

There have been a number of studies on sublexical or subcharacter processing of phonetic radicals in skilled reading of Chinese (Fang, Horng, & Tzeng, 1986; Flores d'Arcais et al., 1995; Hue, 1992; Peng et al., 1994; Seidenberg, 1985; Taft & Zhu, 1997; Zhou, 1994). With few exceptions (Zhou and Marslen-Wilson, 1999a, 1999b), studies of phonetic radicals concentrate on phonological activation of phonetic radicals and its influence on phonological processing of whole characters. Seidenberg (1985) found that regular complex characters, or characters having the same pronunciations as their phonetic radicals, were named faster than frequency-matched simple characters, although this effect was restricted mostly to low frequency characters. Fang et al. (1986) investigated regularity and consistency effects in naming characters, where consistency was defined according to whether *all* complex characters containing a particular phonetic radical are pronounced in the same way as the radical. They observed a significant consistency effect but not regularity effect. Regular-consistent characters (e.g., 材 cai[2], *materials*) were named faster than regular-inconsistent characters (e.g., 油 you[2], *oil*; which contained the phonetic radical 由 you[2], *cause*), although the latter were not named faster than irregular-inconsistent characters (e.g., 抽 chou[1], *lash*). Subsequent studies using similar designs, however, found both regularity and consistency effects for low frequency complex characters (Hue, 1992; Peng et al., 1994).[3]

The effect of sublexical phonological processing and its interaction with the frequency of complex characters were examined more directly in a study using a primed naming task. Zhou and Marslen-Wilson (1999a) used paired characters in which primes were high or low frequency irregular complex characters (e.g., 猜 cai[1], *guess*) and targets were characters (e.g., 轻 qing[1], *light*) that were homophonic to the phonetic radicals (e.g., 青 qing[1], *blue*) embedded in the complex characters but not to the characters themselves. They found that targets preceded by low frequency complex characters were named faster than when they were preceded by unrelated characters. Targets preceded by high frequency complex characters, however, did not show significant facilitation in naming. This pattern of priming effects, together with the regularity and consistency effects in single-character naming, suggests that in processing complex characters, phonetic radicals are decomposed from visual input and used to access their own phonological representations. However, the ability to decompose phonetic radicals and gain access to their phonology is modulated by the frequency of complex characters containing these radicals. Reading high frequency complex characters may involve little decomposition, as the highly efficient processing of whole characters leaves little time for the sublexical processing of their phonetic radicals. Alternatively, the phonological activation of phonetic radicals embedded in complex characters is transient and already suppressed by the phonological activation of whole characters by the time probing targets are presented.

Phonological processing of phonetic radicals and its influences on the processing of whole characters have also been investigated for school children. Shu and Zeng (1996) asked the second, fourth, and sixth grade children to write down, in terms of *pinyin*, the pronunciations of familiar and unfamiliar characters. They found that children's performance was influenced by the regularity of complex characters in relation to their phonetic radicals, with better scores on regular characters than on irregular characters. Children were able to use phonological cues provided by phonetic radicals to guess the pronunciation of unfamiliar characters, and this ability improved as they grew older. Yang and Peng (1997) asked

[3] A potential problem with these studies is that stimuli for different categories were not purposely matched on their initial phonemes in pronunciation. This may explain some of the conflicts between these studies.

participants to name complex characters and recorded their naming latencies. They found that both the third and sixth grade school children showed the consistency effect (as defined in Fang et al., 1986) but only the third grade, not the sixth grade children showed regularity effect. The latter result was probably due to the selection of stimuli. Shu and Wu (1996) used the same design and task as Yang and Peng (1997) and found that both the fourth and sixth grade children showed regularity and consistency effects while the third grade children showed neither of them. In another study, Shu, Zhou, and Wu (in press) asked children to judge whether two characters having the same phonetic radical were homophones. In each pair, the first character was a familiar one while the second character was an unfamiliar one. In guessing the pronunciation of the second character and making judgement, children had to be aware of the orthographic structure of the familiar and unfamiliar characters and use the phonological information provided by the phonetic radical. It was found that children's judgement was influenced by the consistency of phonetic radicals in providing phonological cues to whole characters. Pairs containing consistent radicals were less likely to be judged as non-homophones than pairs containing inconsistent radicals. This effect was pronounced as children were getting older.

All these studies suggest that in reading complex Chinese characters, skilled readers and school children rely on their knowledge about the structure of characters to decompose the visual input of whole characters, and use phonological cues provided by phonetic radicals to help retrieve phonological information of whole characters. Sublexical processing of embedded phonetic radicals, like sublexical processing of letter strings in reading alphabetic words, could be therefore primarily a phonological event, computing phonological output for the whole words (Coltheart et al., 1993; Plaut et al., 1996; Seidenberg & McClelland, 1989).

A study by Zhou and Marslen-Wilson (1999b), however, found that sublexical processing of phonetic radicals activates not only the phonological information corresponding to the radicals, but also the semantic information associated with the radicals. The appearance of complex character 猜 (cai[1], *guess*) activates the semantic representation corresponding to its radical 青 (qing[1], *blue*), leading to facilitation in naming the target character 紫 (zi[3], *purple*), which is semantically related to the phonetic radical, but not to the complex character itself. Moreover, the presence of semantic associates to phonetic radicals also activates the semantic and phonological representations of the radicals, creating phonological competition with the irregular complex characters and delaying the vocalisation of these characters. These findings suggest that sublexical processing of phonetic radicals in reading complex characters is not exactly the same as sublexical processing in reading monomorphemic alphabetic words or semantically opaque compound words, in which the processing of letter strings does not engage semantic activation for the sublexical orthographic units themselves, even when these units happen to be words on their own (e.g., *boy* in *boycott* or *mail* in *blackmail*; see Sandra, 1990; Zhou & Marslen-Wilson, 1999b; Zwitserlood, 1994).

The present study was firstly to examine how children use phonological cues of phonetic radicals embedded in complex characters. Do they treat the phonetic radical-sound correspondences in the same way as the grapheme-phoneme correspondences in alphabetic scripts and compute "prelexical" phonology for whole characters (e.g., Cheng, 1992; Flores d'Arcais et al., 1995)? Or do they decompose the visual input and use phonetic radicals to activate phonological representations of their own as well as characters containing these radicals (Seidenberg, 1985; Zhou & Marslen-Wilson, 1999a)? Secondly, this study was to investigate whether school children's sublexical processing of phonetic radicals is just a phonological event, involving only computing phonology from the decomposed visual input, or is also a semantic event, involving activating semantic information corresponding to these phonetic radicals.

This study used essentially the same designs and technique as Zhou and Marslen-Wilson (1999a,b) to address the above issues. Experiments 1 and 2 examined whether phonetic radicals in complex characters were decomposed by the third and sixth grade children and used to activate phonological representations of these radicals. Experiment 3 examined whether semantic properties corresponding to phonetic radicals were also activated in reading complex characters. In both Experiments 1 and 3, both the third and sixth grade children were tested in order to track the development of sublexical processing.

EXPERIMENT 1

This experiment had two purposes. The first one was to investigate, in children's reading of complex characters, whether phonetic radicals were decomposed from visual input and used to activate their own phonological representations, even though this phonological activation could only interfere with the processing of complex characters themselves. The second purpose was to examine the development of sublexical phonological processing across different ages (or educational levels).

To index the phonological activation of phonetic radicals embedded in complex characters, irregular complex characters (e.g., 海 hai[3], *sea*) were used as primes and characters (e.g., 美 mei[3], *beautiful*) that were homophonic to phonetic radicals (每 mei[3], *every*) embedded in the primes but not to the primes themselves were used as targets (see Table 1). If phonetic radicals are decomposed and used to access their own

TABLE 1
Experiment 1: Design and Sample Stimuli

	Homophone	*Complex*	*Control*	*Target*
Character	每	海	低	美
Pinyin	mei(3)	hai(3)	di(1)	mei(3)
Gloss	*every*	*sea*	*low*	*beautiful*
Frequency	873	270	270	548
Stroke	6.1	9.3	8.8	8.4

Homophone primes are characters embedded in irregular complex primes as phonetic radicals. ‘‘Frequency’’ refers to average frequency of primes or targets (per million). ‘‘Stroke’’ refers to average number of strokes of primes or targets (per character).

phonological representations, the activation of these representations in the lexicon should facilitate the processing of targets, which share phonological properties with the radicals. The reason for using irregular rather than regular complex characters as primes was to make sure that any priming effects were from sublexical or subcharacter processing of phonetic radicals, rather than from lexical level processing of whole characters. It would be impossible to determine the source of facilitation in naming if targets were homophonic to both the whole characters and their phonetic radicals. The same design and stimuli were applied to both the third and sixth grade children.

In this and other experiments, we tested school children of the third and sixth grades. By the third grade, children should have learned large numbers of simple and complex characters (Shu et al., 1998) and have sufficient knowledge about the structure of complex characters and the function of their phonetic and semantic radicals (e.g., Shu et al., in press). Moreover, they can follow instructions to carry out the on-line experimental naming task (Zhou, Wu, & Shu, 1998). The sixth grade children clearly show advantages over lower grade children in their lexical processing. Indeed the pattern of their phonological and semantic processing is very similar to that of skilled adult readers (Zhou et al., 1998), with equally efficient phonological and semantic activation.

Method

Design and Materials. The experimental design and sample stimuli are presented in Table 1. Thirty irregular complex characters with left–right structure were selected from the ‘‘Database of Chinese Characters Learned in School’’, which indexed, according to grades, the first appearance of characters in textbooks used by school children in Beijing. All the selected complex characters were supposed to have been taught to the third grade children. All the phonetic radicals embedded in complex primes were real characters on their own and they were also presented alone as homophone primes. Targets were chosen to be homophonic to the radicals but not to the complex primes. Targets had no orthographic or semantic relations with either complex primes or homophone (or radical) primes.

Another thirty irregular complex characters with left-right structure were also chosen as control primes. There were no orthographic, phonological, or semantic relations between control primes and targets at either lexical or sublexical level. Because our main interest was in phonological priming of phonetic radicals contained in complex primes, control primes were matched in fequency, visual complexity (in terms of the number of strokes), and orthographic structure (left-right composition of phonetic and semantic radicals) with the complex primes, rather than with homophone primes. Since there were no frequency counts for characters used by school children in different grades, the frequency information in Table 1 came from a corpus study of 1.8 million Chinese characters (Institute of Language Teaching and Research, 1986). The familiarity of characters for children was closely correlated to the usage of characters in print (Shu et al., 1998).

Besides the critical stimuli, the experiment also included 50 pairs of filler characters to discourage participants from using potential response strategies. Primes and targets in filler pairs were neither semantically nor orthographically nor phonologically related. Characters used as fillers were of various orthographic structures and with various frequencies. They, and their corresponding phonological forms (i.e., syllables), were not used in the critical stimuli. There were also 20 pairs of practice items, with similar composition as the formal stimuli.

A Latin square design was used to assign the critical primes and their targets into three counter-balanced test versions. In each version, the same targets appeared only once and one third of the targets were preceded by one of the three types of primes. The same filler prime-target pairs were used in the three test versions. A pseudo-random ordering was used to arrange the stimuli in each version, so that, across the test versions, the primes and targets from the same quintets of critical stimuli appeared at the same position in the testing sequence. The SOA between primes and targets was set at 100 ms. At this SOA, school children are capable of producing significant phonological, orthographically, or semantically based priming effects in naming (Wu, 1998; Zhou et al., 1998).

Procedure. The preparation of stimuli was as follows. All primes and targets (in 48 $\times$ 48 *songti* font) were generated by a computer program and stored as individual image files on a hard disk. A character was about

2.4 × 1.6 cm in size. The presentation of stimuli to participants and recording of reaction times were controlled by the dual-screen version software DMASTR, made available to us by Ken Forster. In each trial, an eye fixation signal ("+ ") was first presented at the centre of a computer screen for 300 ms, followed by a 300 ms blank interval. A prime was then presented for 100 ms and overwritten immediately by the corresponding target, which was presented for 400 ms. There was a 3-second interval between the disappearance of the last target and the appearance of the next eye fixation point. Participants were tested individually. They were seated about 60 cm from the screen and were asked to read into a microphone as quickly and as accurately as possible the second character of each trial. The microphone was interfaced with the computer to record voice onset latencies. Participants' performance was monitored by an experimenter and naming errors were recorded by hand in pre-printed scoring sheets.

Each participant saw first a list of 20 prime-target practice items. There was a break after practice. The first three pairs after the break were fillers. The complete test session for each participant lasted less than 15 minutes.

Participants. A total of 82 participants were tested, 39 from the third grade and 43 from the sixth grade. All participants were native speakers of Mandarine Chinese and were school children at the Affiliated School of Beijing Normal University.

Results

Nine participants at the third grade were excluded from analyses because of their high (over 20%) response errors. Three targets were also deleted for the third grade children because over half of participants in one or more test versions made mistakes in response. Mean naming latencies, based on correct responses, were then computed for each participant and each item, and the overall mean reaction times for each condition are presented in the upper part of Table 2.

Overall analyses were first conducted, with the grade as a between-subject factor and prime type as a within-subject factor. The main effect of grade was significant [$F_1(1,71) = 68.29$, $P < .001$; $F_2(1,26) = 182.29$, $P < .001$], indicating that the third grade children were slower than the sixth grade children in naming targets. The main effect of prime type was also significant [$F_1(2,142) = 11.89$, $P < .001$; $F_2(2,52) = 6.77$, $P < .01$]. Post hoc Newman-Keuls tests showed that the mean reaction times for homophone (radical) primes and complex primes were significantly faster than the time for control primes ($P < .01$ and $P < .05$ respectively), indicating that the phonological processing of targets was facilitated both by radical primes

TABLE 2
Experiments 1 and 2: Mean Naming Latencies (ms) and Error Percentages

Experiment	*Grade*	*Homophone*	*Complex*	*Control*
Exp. 1	Third	709 (14.6)	715 (10.0)	756 (10.3)
	Sixth	607 (5.8)	629 (4.5)	628 (5.5)
Exp. 2	Sixth	656 (4.5)	665 (4.5)	690 (3.5)

presented alone as homophone primes and by radicals embedded in irregular complex primes. However, the interaction between grade and prime type was also significant [$F_1(2,142) = 9.19$, $P < .01$; $F_2(2,52) = 3.76$, $P < .05$], suggesting that the priming patterns were not exactly the same for the two grades. The analyses of error rates produced a significant main effect of grade [$F_1(1,71) = 9.25$, $P < .05$; $F_2(1,26) = 10.43$, $P < .05$], with more errors made by the third grade children than by the sixth grade children. The main effect of prime type was not significant [$F_1(2,142) = 1.72$, $P > .1$; $F_2(2,52) = 2.89$, $P > .1$].

Separate analyses were conducted for reaction times for the third and sixth grade children. For the third grade, the main effect of prime type was significant [$F_1(2,58) = 8.36$, $P < .001$; $F_2(2,52) = 7.07$, $P < .01$]. Newman-Keuls tests showed that, against control primes, priming effects for both radical homophone primes and complex primes were significant ($P < .01$), although there was no significant difference between these two ($P > .1$). For the sixth grade, the main effect of prime type approached significance [$F_1(2,84) = 6.83$, $P < .01$; $F_2(2,58) = 2.02$, $.05 < P < .1$]. Newman-Keuls tests showed that the effect for radical homophone primes was significant against control primes ($P < .01$). However, there was no significant difference between complex primes and control primes ($P > .1$).

Discussion

The significant homophone priming effects in the primed naming task, although may have been overestimated due to higher frequency and simpler visual configuration of homophone primes than control primes, were consistent with a number of studies, both with skilled readers (Perfetti & Zhang, 1991; Zhou & Marslen-Wilson, 1999a, in press) and with school children (Wu, 1998; Zhou et al., 1998). These effects indicated that, even for the third grade school children, the pre-activation of phonological information can produce strong facilitatory effects in naming. What is most interesting in this experiment, however, is the finding that irregular complex primes were capable of facilitating the processing of targets that were homophonic not to the primes but to the phonetic radicals embedded in these primes. This sublexical phonological priming effect appeared only for the third grade children, not for the sixth grade children.

The significant priming effect for complex primes demonstrated that in reading complex primes, school children, like skilled readers, decompose the visual input of the whole characters and use their phonetic radicals to activate phonological representations corresponding to the radicals (possibly as well as representations corresponding to other characters containing these radicals), in parallel to the processing of whole characters. Why then did the sixth grade children not show such sublexical phonological activation of phonetic radicals?

As we reviewed earlier, Zhou and Marslen-Wilson (1999a) found that low frequency complex primes, but not high frequency complex primes, facilitated the processing of targets homophonic to the embedded phonetic radicals, consistent with the interaction between regularity and frequency in single-character naming (Hue, 1992; Peng et al., 1994; Seidenberg, 1985). The absence of a significant priming effect for high frequency characters was attributed to the fewer opportunities in decomposing phonetic radicals from high frequency complex characters and/or the strong competition between phonological activation of whole characters and sublexical phonetic radicals. Was it possible that the lack of a significant priming effect for the sixth grade here was because these complex characters had already become high frequency characters for these children? After all, the stimuli were chosen according to their appearance in the third grade textbooks. These complex characters were likely to be used repeatedly after their initial acquisition.

The purpose of the next experiment was therefore to investigate whether sublexical phonological activation of phonetic radicals could be observed for the sixth grade children when complex characters were of relatively low frequency to them.

EXPERIMENT 2

Method

Design and stimuli. The experimental design and critical stimuli were essentially the same as Experiment 1 (see Table 1), except that a few complex primes used in Experiment 1 were replaced with low frequency characters having the same phonetic radicals. All the phonetic radicals (embedded in complex primes and also presented in isolation as homophone primes) and all the targets were the same as those used in Experiment 1. A few control primes were also replaced to match with the new complex primes in frequency and visual complexity. The average frequency of complex primes and the average frequency control primes were both 129 per million. The average numbers of strokes were 10.0 and 9.9 per character respectively for the two types of primes. According to the "Database of Chinese Characters Learned in School", all the new primes had been taught to the sixth grade children.

Procedure. The preparation of stimuli and the test of participants were conducted in the same way as Experiment 1.

Participants. Thirty children of the sixth grade at Beijing Ji Jia Miao school were tested, 10 in each test version. All of them were native speakers of Mandarin Chinese.

Results

Mean naming latencies were computed on the bases of correct responses and they, together with error rates, are reported in the lower part of Table 2. One-way ANOVAs conducted for reaction times revealed a significant main effect of prime type [$F_1(2,58) = 9.31$, $P < .001$; $F_2(2,58) = 6.13$, $P < .01$]. Newman-Keuls tests showed that the mean reaction time for homophone (radical) primes was significantly faster than the time for control primes ($P < .01$). More importantly, the mean reaction time for complex primes was also faster than the time for control primes ($P < .1$ by participants and $P < .05$ by item). The difference between homophone and complex primes was not significant ($P > .1$). The analyses of error rates did not find significant results ($F_1 < 1$, $F_2 < 1$).

Discussion

The finding of a significant priming effect for irregular complex primes for the sixth grade children was consistent with the significant effect for the third grade children in Experiment 1. This effect demonstrated again that in reading complex characters children decompose the phonetic radicals from the whole characters and use them to access their own phonological representations, in parallel to the processing of whole characters. The presence of a significant effect for complex primes, contrasting with the absence of such an effect for the sixth grade children in Experiment 1, also demonstrated that sublexical phonological processing of phonetic radicals is strongly modulated by the frequency of complex characters. Complex primes in this experiment had lower mean frequency than the primes in Experiment 1. Moreover, the sixth grade children tested for this experiment were probably less skilful in reading than the sixth grade children tested for Experiment 1, as demonstrated by the difference (about 50 ms) in average mean reaction times between the two groups.[4] This could mean that the same complex characters were of even lower frequency for the children tested in this experiment than for the children tested in Experiment 1. Phonetic radicals in low frequency complex characters may have more opportunities to decompose and to activate their own phonological representations.

EXPERIMENT 3

The previous two experiments demonstrated that there is a decompositional process in reading complex Chinese characters and that phonological properties associated with the phonetic radicals embedded in complex characters are activated even though this phonological activation can only interfere with phonological activation of whole characters. The ability to decompose characters and conduct sublexical phonological processing develops no later than the third grade; until then school children have acquired about 2000 characters (Shu et al., 1998). The purpose of this experiment was to demonstrate that sublexical processing of phonetic radicals is not only a phonological event, involving computation from orthographic to phonology, but also a semantic event, involving activation of semantic properties associated with the radicals, even though this sublexical semantic activation can only interfere with the processing of whole characters.

In this experiment, irregular complex characters (e.g., 帕 pa[4], *handkerchief*) were used as primes, and characters (e.g., 黑 hei[1], *black*) that were semantically related to the phonetic radicals embedded in these primes (e.g., 白 bai[3], *white*) but not to the primes themselves were used as targets. If reading complex characters involves decomposing phonetic radicals and using them to access their own semantic representations, this sublexical semantic activation should be able to facilitate the processing of targets. Since decomposition and sublexical processing is likely to be

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[4] Children tested in Experiment 1 were from a "key" school in Beijing while children tested in this experiment were from an ordinary school. It was possible that these children had different family backgrounds and there were general differences in educational standard between these schools.

modulated by frequency of complex characters, separate sets of complex primes were used here for the third and sixth grade children.

Method

Design and materials. The design and sample stimuli are presented in Table 3. A total of 60 irregular complex characters (e.g., 帕 pa[4], *handkerchief*) were used as complex primes, 30 each for the third and sixth grade children. These two groups of complex primes, sharing most common characters, had the same set of phonetic radicals (e.g., 白 bai[3], *white*). These radicals were presented on their own as semantic primes. The same sets of targets (e.g., 黑 hei[1], *black*) were used for the two groups of complex primes. Targets were semantically related to the phonetic radicals, but not to the complex primes themselves. All complex primes were of left-right structure with phonetic radicals on the right. Control primes were selected to match with the complex primes on frequency, visual complexity, and orthographic structure. The semantic relatedness between phonetic radicals (i.e., semantic primes) and targets was checked in a pretest, in which 40 children, 20 each from the third and sixth grades, was asked to judge the semantic relatedness on a 7-point scale, ranging from 1 (unrelated) to 7 (highly related). The average points were 5.4 and 5.8 respectively for the third and sixth grade children, indicating that, given time, both the third and sixth grade children can effectively activate semantic properties of radical-target pairs and make conscious judgements.

TABLE 3
Experiment 3: Design and Sample Stimuli

Grade		*Semantic*	*Complex*	*Control*	*Target*
Third	Character	白	拍	泪	黑
	Pinyin	bai(2)	pai(1)	lei(4)	Hei(1)
	Gloss	*white*	*clap*	*tear*	*Black*
	Frequency	807	239	235	1403
	Stroke	5.8	9.3	10.2	9.6
Sixth	Character	白	帕	桶	黑
	Pinyin	bai(2)	pa(4)	tong(3)	Hei(1)
	Gloss	*white*	*handkerchief*	*bucket*	*Black*
	Frequency	807	177	172	1403
	Stroke	5.8	9.6	10.4	9.6

Semantic primes are characters embedded in irregular complex primes as phonetic radicals. ‘‘Frequency’’ refers to average frequency of primes or targets (per million). ‘‘Stroke’’ refers to average number of strokes of primes or targets (per character).

For the two groups of stimuli, a Latin square design was used to assign the critical primes and their corresponding targets into three counterbalanced test versions. Each version in each group had 30 critical targets, 10 of them preceded by one of the three types of primes. Another 50 pairs of characters that were neither semantically, phonologically, nor orthographically related were used as fillers and added to each test version. Characters and syllables used in the critical stimuli were not used again in fillers. A pseudo-random ordering was used to arrange the stimuli so that, across the three test versions in each group, the same targets appeared at the same positions. Twenty pairs of practice items were also used. The SOA between primes and targets was against set at 100 ms.

Procedure. The preparation of stimuli and test of participants were carried out in the same way as Experiments 1 and 2.

Participants. A total of 74 children at Beijing Ji Jia Miao school were tested, 39 from the third grade and 35 from the sixth grade. All of them were native speakers of Mandarin Chinese.

Results

Mean naming latencies and response error percentages are reported in Table 4. ANOVAs were conducted on reaction times, with prime type as a within-subject factor and grade as a between-subject factor. The main effect of grade was highly significant [$F_1(1,67) = 37.56$, $P < .001$, $F_2(1,27) = 260.09$, $P < .001$], indicating that the overall naming latency for the sixth grade children was much faster than the latency for the third grade children. More importantly, the main effect of prime type was significant [$F_1(2,134) = 8.55$, $P < .001$, $F_2(2,54) = 8.46$, $P < .001$]. Newman-Keuls tests showed that the overall naming latency for semantic primes was significantly faster than the latency for control primes ($P < .01$). The overall naming latency for complex primes was also significantly faster than the latency for controls ($P < .05$). The difference between semantic

TABLE 4
Experiment 3: Mean Naming Latencies (ms) and Error Percentages

Grade	*Semantic*	*Complex*	*Control*
Third	714 (7.3)	727 (5.5)	729 (6.6)
Sixth	612 (4.6)	624 (4.6)	645 (4.6)

primes and complex primes was significant ($P < .05$). Moreover, the interaction between prime type and grade was not significant by participants ($F_1 < 1$), but it was marginally significant by items [$F_2(2,54) = 2.60$, $.05 < P < .1$]. Planned tests involving only complex and control primes found a stronger interaction between prime type and grade: [$F_1(1,67) = 2.25$, $P = .1$, $F_2(1,27) = 4.31$, $P < .05$), indicating that although the third grade children exhibited the same trend, as the sixth grade children in semantic and sublexical semantic priming, the priming effect for complex primes was greatly reduced or non-existent for the third grade. Indeed the 2 ms difference between complex primes and control primes for the third grade was not significant. The analyses of error rates did not find a significant main effect of either prime type [$F_1 < 1$, $F_2 < 2$], or grade [$F_1(1,67) = 3.89$, $P = .1$, $F_2(1,27) = 1.19$, $P > .1$].

Discussion

The strong semantic priming effect for the sixth grade children and the non-significant semantic effect for the third grade children were consistent with our other studies (Wu, 1998; Zhou et al., 1998), which had better matched semantic and control primes and which observed essentially the same pattern of semantic priming for children of these two grades. Given the finding that the mean naming latencies for the third grade children were significantly longer than those for the sixth grade, it is reasonable to assume that the third grade children needed more time to process the primes and activate their semantic properties.

The most interesting finding in this experiment was that there was an overall priming effect for complex primes, although this effect came mainly from the sixth grade children. This effect, based on semantic relations between targets and phonetic radicals embedded in complex primes, suggested that in reading complex primes, school children decomposed the phonetic radicals from the visual input of complex primes and used them to activate semantic properties corresponding to the phonetic radicals. This semantic activation spread to the semantic representations corresponding to the target characters, leading to facilitation in naming.

It is clear from Table 4 that the effect for complex primes was greatly reduced, if it did exist, for the third grade children. The absence of significant sublexical semantic activation for the third grade children follows the general weakness of lexical level semantic priming for the third grade children (Wu, 1998; Zhou et al., 1998). It is possible that it requires more processing time for these children to decompose the radicals and activate their semantic properties. The priming effects for semantic and complex primes could be larger when a SOA longer than 100 ms is used.

GENERAL DISCUSSION

In this study, we investigated whether school children, in reading complex characters, engage sublexical processing of phonetic radicals in a way similar to skilled readers and how their sublexical processing is developed over age and schooling. Three experiments, using a primed naming task, found significant priming effects for targets that were either phonologically or semantically related to phonetic radicals embedded in irregular complex primes. In Experiment 1, targets were homophonic to phonetic radicals which were either embedded in complex primes or presented on their own as homophone primes. The same set of stimuli were applied to the third and sixth grade children. Significant priming effects were found for homophone radical primes for children of both grades. However, while the priming effect for complex primes was significant for the third grade children, it was not for the sixth grade children. In Experiment 2, the same design was used on the (possibly less skilled) sixth grade children but with complex primes of lower frequency. Priming effects were significant for both homophone radical primes and complex primes. Experiment 3 used characters that were semantically related to phonetic radicals as targets and complex characters. Significant overall priming effects were found for both semantic (radical) primes and complex primes, although the effect of complex primes was not significant for the third grade children. The patterns of priming effects across the three experiments were, in general, consistent with what were found with skilled adult readers (Zhou & Marslen-Wilson, 1999a,b).

Nevertheless, it seems that there is dissociation between sublexical phonological and sublexical semantic processing of phonetic radicals for the third grade children. This dissociation is indeed parallel to the dissociation between lexical level phonological and semantic processing. There were strong homophone and sublexical phonological priming effects (Experiment 1), in contrast with the weak semantic and sublexical semantic priming effects (Experiment 3). This contrast may be taken as evidence that, for younger children, phonological activation in reading Chinese characters is more efficient than semantic activation, although it is also possible that the larger phonological effects were partly due to the naming task, which is biased towards the use of phonological rather than semantic information.

However, even in such a task, semantic effects were equally strong as phonological effects for the sixth grade children (see Tables 2 and 4). Here we saw equally efficient phonological and semantic activation in reading Chinese (see also Zhou et al., 1998, which compared directly homophone and semantic priming effects for both the third and sixth grade children), similar to what was observed for adult readers (Zhou & Marslen-Wilson, in press). Moreover, sublexical phonological activation of phonetic radicals for these children (Experiments 1 and 2) was modulated by the frequency of complex characters in the same way as for adults (Zhou & Marslen-Wilson, 1999a). The pattern of sublexical semantic activation (Experiment 3) was also similar to the pattern for adults (Zhou & Marslen-Wilson, 1999b). The sixth grade children may have already developed essentially the same structure of the mental lexicon and the same mechanisms of lexical processing as skilled adult readers. This is consistent with the fact that the sixth grade children may have acquired about 3200 characters (Shu et al., 1998), which cover about 99.765% of adult reading materials (Institute of Language Teaching and Research, 1986).

What are the theoretical implications of the priming effects across the three experiments? Clearly, these effects suggest that in reading complex characters, the embedded phonetic radicals are decomposed and mapped onto their own phonological and semantic representations, in parallel to the mapping for whole characters. This sublexical processing is likely to be automatic or mandatory, in the sense that it takes place whether or not it helps lexical processing of whole characters. Indeed, semantic activation of phonetic radicals almost always interferes with semantic activation of whole characters since semantic properties corresponding to phonetic radicals have little in common with those of whole characters containing these radicals.[5] Zhou, Lu, and Shu (in press) found that, for semantic radicals that can stand alone as independent characters, sublexical processing of these radicals activates not only semantic information associated with the radicals (Feldman & Siok, 1999; Zhou & Marslen-Wilson, 1999a), but also phonological information corresponding to the radicals. The presentation of a complex character 躲 (duo[3], *avoid*), for example, facilitates the naming of the target 深 (shen[1], *deep*), which is homophonic to the semantic radical 身 (shen[1], *body*). This sublexical phonological processing of pronounceable semantic radicals embedded in (low) frequency complex characters is another piece of evidence supporting the notion of automatic decomposition in lexical access and parallel processing of whole characters and their constituent radicals.

Thus, sublexical processing of phonetic radicals is both a phonological event, involving computing phonology from decomposed phonetic radicals, and a semantic event, involving activating semantic representations corresponding to the phonetic radicals themselves. There are no fundamental differences between sublexical processing of phonetic (and

[5] When irregular complex characters were used as targets rather than as primes, Zhou and Marslen-Wilson (1999a,b) found that the processing of complex characters is delayed by the presence of semantic associates of their phonetic radicals. This finding suggests that sublexical semantic activation of the embedded phonetic radicals is not under strategic control.

semantic) radicals and lexical processing of simple and complex characters. The proposition treating sublexical processing of phonetic radicals in reading complex characters in the same way as using grapheme-phoneme correspondence in reading alphabetic words is clearly untenable. Lexical processing in reading complex characters is, after all, more analogous to lexical processing of semantically transparent compound words, where semantic properties of both whole words and their constituent morphemes are activated in parallel in reading (Sandra, 1990; Zhou & Marslen-Wilson, 1999b; Zwitserlood, 1994). Moreover, sublexical phonological and semantic processing of phonetic radicals embedded in complex characters has a clear pattern of development over age and schooling.

We believe that sublexical phonological and semantic activation of phonetic radicals in reading complex Chinese characters is partly due to the structure of these characters, the function of the embedded phonetic and semantic radicals, and learning processes in acquiring these characters (Zhou & Marslen-Wilson, 1999b). Structurally, phonetic radicals are integrated orthographic units, whose constituents (e.g., strokes) have no systematic correspondences to phonology or semantics. There are usually clear visual separations between phonetic and semantic radicals, at least for complex characters with left-right structure. This provides clear cues for visual decomposition of phonetic and semantic radicals in lexical access. Functionally, both phonetic and semantic radicals can have their own semantic properties. Most phonetic radicals and some semantic radicals also have their own phonological properties. Phonetic radicals are not only meaningful characters by themselves, being acquired very early in learning and having much higher frequency than complex characters containing them (Shu et al., 1998), but also repeatedly used in different characters. Complex characters are therefore more similar to compound words rather than to monomorphemic words, having functionally salient components. Furthermore, the relations between phonetic and semantic radicals and the complex characters are either explicitly or implicitly taught to children when they learn characters. For example, one way to teach children to learn characters, used by some parents and in some schools in mainland China, is to group together characters with the same phonetic (or semantic) radicals and ask children to pay special attention to the structure and composition of these characters. Also, since a common way for Chinese dictionaries to arrange characters is to group characters according to their orthographic structure and common components (usually semantic radicals) and to use these components as indexes, school children and adult readers have to decompose characters and use their critical component a searching cues when they use dictionaries.

All these properties make phonetic radicals very salient orthographic and functional units in complex characters. Decomposing such units from visual input and activating their corresponding phonological and semantic properties in the lexicon thus becomes not only natural but also mandatory. The parallel processing of whole characters and sublexical radicals appears not only in skilled reading, but also in the early stage of learning.

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