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The second-order effect of orthography-to-phonology mapping consistency on Chinese spoken word recognition

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ABSTRACT

The influences of the orthography-to-phonology (O-to-P) mapping consistency as the first-order effect on visual word recognition are well documented. Few studies have investigated the second-order O-to-P consistency effect on spoken word recognition. To address this issue, Experiment 1 asked participants to perform a writing-to-dictation task for 230 Chinese monosyllabic words and found that the response accuracy increased with the homophone density, and the homophone density, O-to-P consistency, and character frequency also affected the generation probability and reaction time of written responses. Experiment 2 involved manipulating the homophone density of the spoken words and the O-to-P consistency of the written characters in writing to dictation with event-related potential measurement. The data revealed an interactive effect between the O-to-P consistency and homophone density on frontal-central N400 and a homophone density effect on the posterior late positivity component. The results support the reverberation effect of the O-to-P consistency on Chinese spoken word recognition.

1. Introduction

Reading ability is one of the most important skills that children must acquire, while speech is acquired much earlier than reading ability in an individual's life. Evidence from psycho- and neuro-linguistic studies generally agrees that literacy acquisition is a process for understanding how written forms map onto preexisting phonological (speech sound) and semantic (meaning) representations. Models for word recognition, such as the interactive activation model (McClelland & Rumelhart, 1981), parallel-distributed connectionist models (Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989), and the bimodal interactive activation model (BIAM) (Grainger & Ziegler, 2008), assume that efficient word recognition relies on connections among orthographic, phonological, and semantic codes. In particular, the BIAM assumes that the mapping between orthography (O) and phonology (P) can be measured bidirectionally, namely as the O-to-P mapping consistency (i.e., whether orthography is pronounced consistently) and the P-to-O mapping consistency (i.e., whether phonology is spelled consistently). Studies on various languages have demonstrated the O-to-P consistency effect on visual word recognition (Fang, Horng, & Tzeng, 1986; Jared, 1997, 2002; Jared, McRae, & Seidenberg, 1990; Lee et al., 2004, 2007; Lee, Tsai, Su, Tzeng, & Hung, 2005), and the P-to-O consistency effect on spoken word recognition (Chen, Chao, Chang, Hsu, & Lee, 2016; Chereau, Gaskell, & Dumay, 2007; Pattamadilok, Kolinsky, Luksaneeyanawin, & Morais, 2008; Pattamadilok, Morais, Ventura, & Kolinsky, 2007; Taft, Castles, Davis, Lazendic, & Nguyen-Hoan,

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2008; Ziegler, Petrova, & Ferrand, 2008). However, an issue still under debate is whether visual and auditory word recognition is affected by the O-to-P and P-to-O consistencies in both directions. Based on the recurrent network for word recognition, spoken word recognition is influenced by not only the P-to-O consistency but also the O-to-P consistency. However, relatively few studies have reported observing the O-to-P consistency effect on auditory modality. Thus, the current study addressed this issue further by investigating whether the O-to-P mapping consistency plays a role in Chinese spoken word recognition.

1.1. First-order mapping consistency effect in alphabetic languages

Visual word recognition is a process for retrieving semantic and phonological information from orthographic inputs. The impact of the O-to-P consistency on visual word recognition is expected. Studies of alphabetic writing systems have defined the O-to-P consistency as the degree to which similarly spelled words are pronounced similarly (i.e., –eap is consistent in that it is pronounced as /ip/ only, whereas –ave is inconsistent since it can be sounded as either /æv/ or /eiv/). A well-established finding is the O-to-P consistency effect in word naming, in which the responses in naming O-to-P consistent words were faster and more accurate than those for inconsistent words (Glushko, 1979; Jared, 1997, 2002; Jared et al., 1990). These findings support the obligatory activation of phonology during visual word recognition.

In contrast, spoken word recognition is a process for retrieving semantic information from phonological inputs. Given that speech is acquired much earlier than reading, and that the link between phonology and semantics is well established before one learns to read, there seems no obvious advantage in activating a word's orthography during spoken word recognition. However, a large amount of evidence has demonstrated that orthographic information plays a role in spoken word recognition. For example, Seidenberg and Tanenhaus (1979) demonstrated that rhyme judgments for spoken words were delayed when the rhyming stimuli were orthographically dissimilar (*pie-rye* vs. *pie-tie*). Furthermore, the P-to-O consistency can be measured to determine whether words have onsets or rimes that can be spelled in multiple ways (e.g., /^k/ is consistent since it has only one spelling, –uck, whereas /ip/ is inconsistent in that it can be spelled either –eep or –eap). The P-to-O consistency effect in auditory modality has been replicated in multiple languages (Chereau et al., 2007; Pattamadilok et al., 2007, 2008; Taft et al., 2008; Ziegler et al., 2008). A typical finding has been that P-to-O inconsistent words take longer to be identified and yield more errors than P-to-O consistent words do in auditory lexical decision tasks. These findings have been used to support that orthographic information is activated during spoken word recognition.

1.2. Second-order mapping consistency effect in alphabetic languages

Intriguingly, Stone, Vanhoy, and Van Orden (1997) manipulated both the O-to-P and P-to-O consistencies in a visual lexical decision task. The results not only replicated the O-to-P consistency but also demonstrated a P-to-O consistency effect in reading O-to-P consistent words. The existence of the feedback P-to-O consistency effect on visual word recognition is critical, because the traditional bottom–up theories of word recognition do not predict the presence of a second-order effect. This finding has been used to support the bidirectional coupling of the adaptive resonance model (Stone & Van Orden, 1994), suggesting that when a word is read, the activated phonology recurrently activates the word's corresponding orthographic form, and the inconsistent P-to-O mapping retards visual word recognition.

However, it remains unclear whether the P-to-O consistency effect can be reliably found in visual modality across languages that vary in the degree of P-to-O consistency. For example, the P-to-O consistency effects in visual lexical decision and naming tasks have been replicated in French (Ziegler, Montant, & Jacobs, 1997) and English (Lacruz & Folk, 2004; Massaro & Jesse, 2005; Perry, 2003). Peereman, Content, and Bonin (1998) replicated the P-to-O consistency by using items from Ziegler et al. (1997); however, the effect disappeared when they further controlled for subjective familiarity. Lacruz and Folk (2004) reported observing the P-to-O consistency effect in visual lexical decision and naming tasks while controlling for word frequency, familiarity, and other variables such as the word length, orthographic neighborhood, bigram frequency, and summed frequency of friends. Nevertheless, Ziegler et al. (2008) did not find the P-to-O consistency effect in visual lexical decision with orthogonally factorial manipulation of both the O-to-P and P-to-O consistencies at the rime level.

It appears that the P-to-O consistency effect can be reliably found in spoken word recognition but is more difficult to observe in visual word recognition. One of the potential reasons is that the P-to-O consistency is more direct in auditory modality because it requires only a simple "one-way" feedback from phonology to orthography (i.e., coactivation); thus, it has also been determined to be a first-order effect on spoken word recognition. In contrast, the P-to-O consistency effect is less direct and serves as a second-order effect on visual word recognition. Reading a word would firstly activate its phonology, and then feed back to its orthography (Ziegler et al., 2008). In addition, previous studies have used the orthogonal manipulation of the P-to-O and O-to-P consistencies, often resulting in a small number of items per condition (e.g., eight items per cell, as in Lacruz and Folk (2004)). Thus, it might be more effective to examine the P-to-O consistency effect in a large-scale database. Balota, Cortese, Sergent-Marshall, Spieler, and Yap (2004) applied hierarchical regression analysis on the naming and lexical decision latencies of 2428 monosyllabic English words to examine the contribution of the O-to-P and P-to-O consistencies at both the rime and onset levels. Their results revealed significant O-to-P and P-to-O consistency effects at the rime level in both naming and lexical decision.

To summarize, the P-to-O consistency effect on visual word recognition has been used to support the notion of bidirectional coupling between orthography and phonology in word recognition. Meanwhile, although the O-to-P consistency effect is observed in visual word recognition, few studies have examined the second-order O-to-P consistency effect on spoken word recognition. For example, Davies and Weekes (2005) found an advantages of O-to-P consistent words over O-to-P inconsistent ones in spelling accuracy in both typically developing and dyslexic children, especially for spelling high P-to-O consistent words. Nevertheless, such a result has not been replicated in studies on developing readers across languages (Lete, Peereman, & Fayol, 2008; Spencer, 2007; Weekes, Castles, & Davies, 2006). Ziegler et al. (2008) orthogonally manipulated the P-to-O and O-to-P consistencies in an auditory lexical decision task, in which only the P-to-O consistency effect was found on reaction time. Therefore, it remains unclear whether the O-to-P consistency effect exerts a second-order effect on spoken word recognition.

1.3. First-order mapping consistency effect in Chinese

Chinese is considered a morphosyllabic writing system. However, all writing symbols were conceived to represent speech, In Chinese, approximately 80% of Chinese characters are phonograms (e.g., 踩, *cǎi*, "to step on") consisting of a semantic radical that provides information for meaning (e.g., 足, *zú*, "foot") and a phonetic radical that provides information for pronunciation (e.g., 采, *cǎi*, "gathering"). The O-to-P mapping consistency of Chinese phonograms has been defined as the agreement of a character's pronunciation with those of its orthographic neighbors containing the same phonetic radical, to describe the phonological relationship between a phonogram and a phonetic radical. For example, 搖 (*yáo*) has six orthographic neighbors; namely, 鷂, 瑤, 遙, 徭, 傜, and謠, all of which share the same pronunciation (*yáo*). On the other hand, although 流 (*liú*) also has six orthographic neighbors, 琉 (*liú*) and 硫 (*liú*) are its "friends," but 梳 (*shū*), 疏 (*shū*), and 毓 (*yù*) are not. Therefore, 搖 and its orthographic neighbors are high O-to-P consistency characters (consistency index = 1), whereas 流, 琉, and 硫 are low O-to-P consistency characters (consistency index = 0.33). Notably, the definitions of consistency in English and Chinese are parallel concerning the representation of the statistical relationship between orthographic forms and their pronunciations. The O-to-P consistency effect in reading Chinese has been well established in behavioral and neuroimaging studies. Low-consistency characters have prompted slower and less accurate naming responses (Fang et al., 1986; Lee et al., 2004, 2005) and have elicited greater brain activations in the left inferior frontal gyrus, the left temporo-parietal region, and the left temporo-occipital junction then high-consistency characters do, especially for those with low character frequency (Lee, Huang, Kuo, Tsai, & Tzeng, 2010; Lee et al., 2004). Other studies have demonstrated that native-Chinese-speaking readers could capture the O-to-P mapping consistency in homophone judgment (Chiu, Kuo, Lee, & Tzeng, 2016; Lee et al., 2007; Lee, Tsai, Huang, Hung, & Tzeng, 2006) and sentence reading (Tsai, Lee, Tzeng, Hung, & Yen, 2004); this ability was also observed in hearing-impaired users of sign language in Taiwan (Chiu et al., 2016).

Moreover, Chinese characters represent monosyllabic (and usually monomorphemic) forms, with the majority consisting of a consonant-vowel structure. Given their relatively simple syllabic structure, most Chinese syllables may represent more than one morpheme and map onto more than one orthographic form (character). The pervasive homophony of Chinese indicates a greater impact from orthography during Chinese spoken word recognition. However, only a few studies have examined how the P-to-O consistency affects spoken word recognition. Lee, Hsu, Chang, Chen, and Chao (2015) suggested that the mapping variations from phonology to orthography can be considered at character and radical levels. The former is the homophone density, which is defined as the number of characters sharing the same pronunciation (including tonal characteristics). The latter is the orthographic consistency, which is defined as whether a set of homophones can be divided into subgroups based on their sublexical orthographic units (phonetic radicals). Wang, Li, Ning, and Zhang (2012) found that high homophone density words elicited slower responses than low homophone density words did in an auditory lexical decision task. Chen et al. (2016) used the event-related potential (ERP) technique to investigate how both types of P-to-O mapping variations affect Chinese spoken monosyllable word recognition in a semantic categorical task and demonstrated the orthographic consistency effect on N400 and the homophone density effect on the late positivity component (LPC). These results support the impact of orthography on Chinese spoken word recognition.

1.4. Second-order mapping consistency effect in Chinese

In addition to the aforementioned first-order consistency effects, namely the O-to-P consistency effect on Chinese visual word recognition (Fang et al., 1986; Lee et al., 2004, 2005) and the P-to-O effect on Chinese spoken word recognition (Chen et al., 2016; Wang et al., 2012), some studies have demonstrated the second-order P-to-O mapping consistency effect in the reading of Chinese characters (Chen, Vaid, & Wu, 2009; Lee et al., 2015; Tan et al., 2001; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). Some studies have reported observing facilitative homophone density effects on naming and lexical decisions involving Chinese characters (Chen et al., 2009; Tan et al., 2001; Ziegler et al., 2000). Lee et al. (2015) applied linear mixed model (LMM) analyses on lexical decision responses for 3423 Chinese phonograms. The data revealed a facilitative effect of orthographic consistency and an inhibitory effect of homophone density on lexical decision latencies. Overall, although the patterns of the homophone density effect remain controversial across tasks, these findings support that phonological activation reverberates to orthographic representation in Chinese visual word recognition.

According to the adaptive resonance model (Grainger & Ziegler, 2008; Stone & Van Orden, 1994), the orthographic representation activated by spoken word recognition sends feedback to its phonology. Therefore, the O-to-P consistency also plays a role in spoken word recognition. Han, Song, and Bi (2012) used multiple regression analyses to investigate whether potential variables affect the cognitive mechanism underlying the writing to dictation of Chinese monosyllabic words. They determined that character frequency, imageability, and homophone density predict the probability of a specific character from a set of homophones being written for the target syllable. In addition, they also found that the phonetic radical transparency (defined as whether the pronunciations between the whole character and its phonetic radical are the same according to onset, rime, or tone) also affects the performance of writing to dictation and thus supports the existence of a feedback loop from orthography to phonology in spoken word recognition. However, they determined that the O-to-P consistency effect in writing to dictation was not significant. Leung, Lui, Law, Fung, and Lau (2013) had 2194 students from Grades 1 to 6 perform a writing-to-dictation task involving characters presented in word contexts. The target characters were manipulated based on their homophone density and O-to-P consistency with a factorial design. The data revealed an inhibitory homophone density effect on writing accuracy from Grades 2 to 6. However, the O-to-P consistency effects were quite unstable across grades. The children from Grade 2 to 5 showed facilitative O-to-P consistency effects for the words with high homophone density, but children from Grade 2 to 6 revealed inhibitory O-to-P consistency effects for the words with low homophone density. Taken together, it remains unclear whether the second-order O-to-P consistency effect can be reliably found and how it could be modulated by the first-order P-to-O mapping consistency during Chinese spoken word recognition.

This study examined whether the O-to-P consistency affects Chinese spoken word recognition in writing-to-dictation tasks. Because most Chinese syllables can be mapped onto a set of homophones, researchers cannot manipulate the O-to-P consistency unless they can predict which character listeners will choose from a set of homophones for writing to dictation on hearing a Mandarin syllable. Therefore, we first conducted a norming study to assess college students' writing-to-dictation performance in using 230 Chinese monosyllabic spoken words. This corpus enables estimating the probabilities of a set of Chinese characters being generated as written responses when participants hear Chinese spoken words. Experiment 2 entailed utilizing such a database to manipulate the homophone density of Chinese monosyllabic spoken words and the O-to-P consistency of characters with the highest generation probability in a writing-to-dictation task with ERP measurement. ERP data should elucidate when and how the second-order O-to-P consistency plays a role in Chinese spoken word recognition.

2. Experiment 1: norming study

The norming study was conducted to provide a database for assessing the writing-to-dictation responses of 230 Chinese monosyllabic words. In addition, the LMM was used to examine how the syllable frequency, homophone density, P-to-O consistency, character frequency, O-to-P consistency, and number of strokes affect the generation probability and reaction time of a specific character selected from a set of homophones in Chinese writing to dictation.

2.1. Methods

2.1.1. Participants

Sixteen right-handed native-Chinese speakers with normal or corrected-to-normal vision and hearing, and with no neurological or psychiatric diseases, participated in Experiment 1 (7 male, aged 20–30 y, mean 25 ± 3.4 y). Informed written consent was received from all the participants.

2.1.2. Materials

In this study, 230 monosyllabic Chinese spoken words were chosen from Lee et al. (2015). The inclusion criteria are as follows, (1) the log-transformed syllable frequency shall higher than 0.9, (2) should not be homographs, (3) to optimize the manipulation on homophone density in Experiment 2, syllables with high homophone density should have at least two high-frequency characters (≥500/per million) among a set of homophones. Ideally, all the variables of the chosen syllables should tend toward linear distribution. However, in this study, when homophone density and O-to-P consistency were spread linearly, the P-to-O consistency was restricted to high inclination. Consequently, the P-to-O consistency of the syllables was controlled (higher than 0.9) and excluded from further statistical analyses. For the selected 230 monosyllabic Chinese spoken words, the log-transformed syllable frequency was ranged from 0.95 to 5.04 (mean 3.20, SD = 0.87), the homophone density was ranged from 1 to 12 (mean 3.35, SD = 2.42), and the P-to-O consistency was ranged from 0.9 to 1 (mean 0.96, SD = 0.14).

2.1.3. Writing-to-dictation task

In the writing-to-dictation task, each participant heard 230 monosyllabic Chinese spoken words, all of which were digitally recorded by a female native-Chinese speaker in a soundproof studio. The stimuli were further normalized to 70 dB and 650 ms by using Adobe Audition®. The participants were tested individually in a quiet room. The monosyllabic words were presented binaurally through headphones connected to a notebook computer. The participants first received 20 practice trials and then 230 experimental trials, which were subdivided into five sessions (i.e., 46 randomized experimental trials per session). The participants were permitted to take a break between test sessions for as long as they needed. The trials were begun with a fixed cross appearing on the central screen for 500 ms. The participants then heard a 650-ms target word while the fixed cross remained on the screen, and they were asked to write the first corresponding written character that came to mind as soon as possible on a tablet (Wacom Bamboo Pen CTL-470). The participants were then asked to click the mouse to initiate the next trial. The reaction times (in milliseconds) from the onset of the sound to the contact of the pen with the tablet, as well as the written responses, were recorded for further analyses.

2.1.4. Norming database

For the norming database, the properties of spoken words, including syllable frequency, homophone density, and P-to-O consistency, and the corresponding written responses that all the participants generated were coded in the norming database. Based on Lee et al. (2015), *syllable frequency* refers to the accumulation of homophones' character frequency and was logarithmically transformed. *Homophone density* is defined as the number of characters sharing the same pronunciation (including tonal characteristics). *P-to-O consistency* refers to the ratio of the summed frequencies of homophones sharing the same phonetic radical to the summed frequencies of homophones.

Table 1
Normative data of the norm for generation probability (%).

Spoken words				Written responses					
Syllable	Syllable frequency	Homophone density	P-to-O consistency	Number of participants	Character (meaning)	O-to-P consistency	Character frequency	Number of strokes	Generation probability
dèng	2.95	5	1	7	瞪 (stare)	0.6	1.83	17	44
				4	鄧 (surname)	0.6	2.9	15	25
				2	蹬 (pedal)	0.6	0.3	19	13
				1	凳 (bench)	0.6	1.45	14	6

For the written responses, the O-to-P consistency, character frequency, and number of strokes were also coded in the database. *O-to-P consistency* refers to the proportion of the number of characters containing the same phonetic radical that have the same pronunciation (excluding tonal characteristics) to the number of characters containing that phonetic radical. *Character frequency* refers to the frequency of a character per million based on the Academia Sinica Balanced Corpus (Huang & Chen, 1998), and was logarithmically transformed. In addition, the generation probability and reaction time of the written responses were also coded in the database. The generation probability of each correct response was measured as the number of participants producing a particular character divided by the total number of participants, to index the probability of that character being generated for a given syllable target (Han et al., 2012). Take the syllable dèng for example: Among the responses produced by the 16 participants were 14 correct responses (7瞪, "stare"; 4鄧, "surname"; 2蹬, "pedal"; 1凳, "bench") and 2 writing errors. Thus, the generation probabilities of four correct characters—瞪, 鄧, 蹬, and凳—were 44% (7/16), 25% (4/16), 13% (2/16), and 6% (1/16), respectively.

In summary, for each syllable, the norm listed the correct character responses produced by the 16 participants, to show the value of predictors and generation probability of all the correct characters (Table 1).

2.1.5. Statistics

We evaluated how the properties of spoken words, including homophone density and syllable frequency, influenced the participants' ability to produce correct written responses for the 230 Chinese monosyllabic words. If a participant correctly wrote any character from a set of corresponding homophones, then the written response was considered correct and coded as 1. Otherwise, the response was considered a writing error and coded as 0. We then used a generalized linear mixed-effects model (GLMM) to determine the accuracy (1 or 0) of written responses elicited from 16 participants for the 230 Chinese monosyllabic words as a dependent variable. The GLMM with logistic regression was estimated by including the participants and syllables as a random effect, and the syllable frequency and homophone density as the fixed factors. The GLMM analysis was performed using the glmer function from the lme4 package (Bates, Mächler, Bolker, & Walker, 2014) in the R environment (R Development Core Team, 2015). The mean error rate for all the participants was 23.3% (SD = 7.3%, ranging from 11.7% to 33%). The error responses included the following types: (1) null responses (mean 5.1%, SD = 3.6%, ranging from 0.9% to 10.9%), (2) characters associated with a potential character that corresponds to the target syllable (mean 2%, SD = 1.3%, ranging from 0.4% to 3.9%) (3) writing errors (e.g., stroke deletion or insertion, or phonologically related errors), (mean 16.2%, SD = 6%, ranging from 5.7% to 27.8%).

Moreover, to further examine how the syllable frequency, homophone density, P-to-O consistency, O-to-P consistency, character frequency, and number of strokes play roles in writing to dictation, we performed LMM analyses on the generation probability and reaction time of each written character as dependent variables. As presented in Table 1, the database provided the generation probability of each written character elicited from the 230 Chinese monosyllabic words. The LMMs for generation probability were estimated by including the syllables as a random effect. Besides, the database for reaction time provided the reaction time elicited from 16 participants for a set of written responses. The LMMs for generation probability were estimated by including the participants and items (written responses) as random effects.

Mode1 1 included syllable frequency and homophone density as fixed effects for evaluating how these two properties of spoken words influence the reaction time and generation probability for a specific character chosen from a set of homophones. Model 2 added additional predictors of written characters, including the character frequency, O-to-P consistency, and number of strokes, and the interaction between homophone density and O-to-P consistency into Model 1. If the interaction effect was not significant, then the interaction term was excluded and Model 2 was refitted. Likelihood ratio tests and χ^2 distributions were used to evaluate whether the added predictors significantly improved the fits. The coefficients (β), associated standard errors (*SE*), and *t* values of fixed effects were estimated using the lmer function from the lme4 package in the R environment. Fixed effects exhibiting |t|s > 2 were considered significant (Baayen, 2008).

2.2. Results

2.2.1. GLMM for accuracy

All 16 participants completed the writing-to-dictation task with 230 monosyllabic Chinese spoken words, and produced 2822 correct responses and 858 error responses. The GLMM analysis involved examining the contribution of syllable frequency and homophone density in predicting the accuracy of written responses for each spoken word. The results revealed a significant effect of homophone density (Z = 249.27, p < 0.001), although the effect of syllable frequency was not significant (Z = 0.014, p = 0.6). The

Table 2
Means, standard deviations, and correlation coefficients of the predictors for generation probability and reaction time.

	Generation probability					Reaction time				
	Mean (SD)	SF	HD	OPC	CF	Mean (SD)	SF	HD	OPC	CF
Syllable frequency (SF)	3.34 (0.78)					3.29 (0.73)				
Homophone density (HD)	4.14 (2.61)	0.544***				3.44 (2.49)	0.517***			
O-to-P consistency (OPC)	0.53 (0.33)	0.034	0.136*			0.50 (0.33)	−0.063**	0.040		
Character frequency (CF)	2.7 (0.84)	0.509***	0.125*	0.017		3.01 (0.72)	0.693***	0.193***	−0.061**	
Number of strokes	12.19 (3.74)	0.014	0.019	0.077	−0.109	11.89 (3.63)	0.034	0.051*	0.039	−0.057**

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

estimated data showed that the accuracy increased with the increased homophone density.

2.2.2. LMMs for generation probability

For the LMM analyses for the generation probability, the four types of error responses, which descripted in the section of statistics, were excluded. Take the syllable *hóu* for example: 12 participants produced correct responses (8猴, *hóu*, “monkey”; 3喉, “throat”; 1侯, “marquis”), two participants provided a null response, one of them wrote the associated character (頭*tóu*, “head” the second character of喉頭 *hóu tóu*, “larynx”), and one of them wrote the phonologically related character (吼 *hǒu*, “roar”). Since the O-to-P consistency is inapplicable to nonphonograms, they (mean 9.8%, SD = 1.7%, ranging from 6.5% to 13.5%) were also excluded from further LMM analyses. Ultimately, 2461 correct written responses, corresponding to 318 distinct characters, were included in the LMM analyses of the generation probability. Table 2 displays the means, standard deviations, and correlation coefficients of the predictors for generation probability and reaction time.

These LMM analyses entailed examining the contribution of the syllable frequency, homophone density, O-to-P consistency, character frequency, and number of strokes in predicting the generation probability of the written responses. The fixed effects of the LMMs for generation probability in Models 1 and 2 are shown in Table 3 (A). In Model 1, the effect of homophone density was significant ($|t| = 7.56$, $p < 0.001$), whereas the effect of syllable frequency was not significant ($|t| = 1.245$, $p = 0.212$). The beta values indicated that the generation probability decreased with the increased homophone density. For Model 2, the nonsignificant interaction between homophone density and O-to-P consistency was excluded and then refitted. The likelihood ratio test indicated a significant improvement after inclusion of written characters’ properties such as the O-to-P consistency, character frequency, and number of strokes in Model 2 ($\chi^2 = 91.165$, $p < 0.001$). The results revealed significant effects of syllable frequency, homophone density, and character frequency ($|t|s > 2$, $p < 0.001$), whereas the effects of O-to-P consistency and the number of strokes were not significant ($|t| < 2$, $p > 0.05$). The beta values indicated that the generation probability of a character increased with the

Table 3
Linear mixed model estimates of the fixed effects for (A) generation probability and (B) reaction time.

(A) Generation probability

	Model 1			Model 2		
Variables	Beta	Std.Error	*t*-value	Beta	Std.Error	*t*-value
(Intercept)	61.736	7.470	8.265	51.807	8.559	6.053
Syllable frequency	3.172	2.548	1.245	−10.814	2.628	−4.115***
Homophone density	−5.791	0.766	−7.560***	−4.193	0.689	−6.082***
O-to-P consistency				−7.727	4.458	−1.733$^+$
Character frequency				20.675	2.095	9.869***
Stroke				−0.248	0.395	−0.627
likelihood ratio tests				$\chi^2 = 91.165$ $p < .001$		

(B) Reaction time

	Model 1			Model 2		
Variables	Beta	Std.Error	*t*-value	Beta	Std.Error	*t*-value
(Intercept)	879.889	83.036	10.596	873.077	82.866	10.536
Syllable frequency	−171.012	25.247	−6.774***	−47.456	31.143	−1.524
Homophone density	24.528	7.509	3.266**	14.181	7.310	1.940$^+$
O-to-P consistency				−111.215	46.177	−2.408*
Character frequency				−168.024	26.698	−6.294***
Stroke				6.605	4.185	1.578
likelihood ratio tests				$\chi^2 = 47.737$, $p < .001$		

$^+p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

increased character frequency and the decreased syllable frequency.

2.2.3. LMMs for reaction time

In this study, the average reaction time for participants is 846.73 ms (SD = 79.91 ms) and for item is 879.30 ms (SD = 172.95 ms). For the LMM analyses of reaction time, the trials with reaction times longer than two standard deviations above the mean for the participants (mean 3%, SD = 0.8%, ranging from 1.3% to 4.8%) and items (mean 3%, SD = 4.6%, ranging from 0.4% to 13.9%) were excluded. Ultimately, 2242 trials, corresponding to 304 characters, were included in the LMM analyses of reaction time. Table 3 (B) shows the results of the fixed effects in Models 1 and 2. The results of Model 1 revealed significant syllable frequency and homophone density effects ($|t|s > 2$, $p < 0.01$). The beta values indicated that the longer time for generating written responses for the monosyllables is associated with decreased syllable frequency or the increased homophones density. For Model 2, the nonsignificant interaction between the homophone density and O-to-P consistency was excluded from Model 2 and then refitted. The likelihood ratio test indicated a significant improvement after inclusion of the written characters' O-to-P consistency, character frequency, and number of strokes in Model 2 ($\chi^2 = 47.737$, $p < 0.001$). The results showed significant effects of the O-to-P consistency and character frequency ($|t|s > 2$, $p < 0.05$) and a marginally significant effect of the homophone density ($|t| = 1.94$, $p = 0.05$). However, the effects of syllable frequency and number of strokes were not significant ($|t|s < 2$, $p > 0.1$). The beta values of Model 2 indicated that characters with higher O-to-P consistency showed a faster reaction time than did those with lower O-to-P consistency. High-frequency characters revealed faster responses than low-frequency characters did.

2.3. Discussion

Experiment 1 was performed to establish a database for writing to dictation of 230 Mandarin monosyllabic words and to investigate how the syllable frequency, homophone density, character frequency, and O-to-P consistency affect the generation probability and reaction time in Chinese writing to dictation.

2.3.1. Effects on generation probability

The LMM analysis of the generation probability showed inhibitory effects of the homophone density and syllable frequency. The generation probability of a character decreased with the increased homophone density. This result also replicated the findings of Han et al. (2012), who showed that a character with more homophones was less frequently produced. These findings suggest that a larger homophone density may result in greater competition for choosing a specific character for a written response. Since the syllable frequency is the cumulative character frequency of all homophones, the syllable frequency is highly positively correlated with the homophone density, as shown in Table 2. The syllable frequency effect also showed an inhibitory effect, as the homophone density did, which was expected. Moreover, Model 2 showed a facilitative character frequency effect on generation probability, which is in line with the results of Han et al. (2012). The participants in the current study were more likely to generate the writing of high-frequency characters than that of low-frequency characters in Chinese writing to dictation. In our writing-to-dictation task, the participants were asked to write only one character for the corresponding monosyllabic spoken word. Thus, the participants tended to produce a high-frequency character from a set of homophones.

2.3.2. Effects on reaction time

The results of reaction time showed a facilitative syllable frequency effect and an inhibitory homophone density effect. It was easier for the participants to write corresponding characters when they heard monosyllabic words with high syllable frequency. However, it took more time for them to write a character if the spoken word could be mapped onto many homophones. These results are consistent with previous findings on auditory lexical decision tasks (Wang et al., 2012) and semantic categorization tasks (Chen et al., 2016). These studies have suggested that words with high homophone density activate more orthographic representations and thus lead to a stronger orthographic or semantic competition during auditory recognition. In the current writing-to-dictation task, increased homophone density led to prolonged response latencies.

Model 2 further considered the properties of written characters, including the O-to-P consistency, character frequency, and number of strokes. The results of Model 2 revealed a facilitative character frequency effect on the reaction times. The participants initiated the writing of high-frequency characters faster than that of low-frequency characters in Chinese writing to dictation. This finding is congruent with those of previous research on writing (Bonin & Fayol, 2002; Bonin & Meot, 2002; Bonin, Peereman, & Fayol, 2001; Delattre, Bonin, & Barry, 2006). However, when character frequency was taken into account, the homophone density and syllable frequency effects were no longer significant in Model 2. Andrews (1997) reported that the orthographic neighborhood size (defined as the number of words that can be created by changing a single letter in a target word while maintaining the original positions of the letters) may have a facilitative or inhibitory effect on visual word recognition, depending on the level of processing. For words with larger orthographic neighborhoods, there is more global activation in the mental lexicon that facilitates lexical decisions, which can be made even before lexical identification is fully complete, especially when the task stresses speed over accuracy (Grainger & Jacobs, 1996). For tasks that stress accuracy or require deep processes such as accessing a word's meaning, words with large orthographic neighborhoods tend to exhibit an inhibitory effect (Forster & Shen, 1996; Grainger & Jacobs, 1996; Pollatsek, Perea, & Binder, 1999). Therefore, for our writing-to-dictation task, which required producing orthographic representations, the high homophone density words with high orthographic and semantic neighbors led to an inhibitory effect in Model 1. However, the neighborhood size effect is usually negligible or nonexistent for high-frequency words (Andrews, 1989; Forster & Shen, 1996; Pollatsek et al., 1999). Previous studies have demonstrated that the primary influence of a neighborhood is not the neighborhood size but the frequency of a word's neighborhood relative to its own frequency. The presence of a high-frequency neighbor in a neighborhood slows the target's lexical access (Grainger, O'Regan, Jacobs, & Segui, 1989; Huang et al., 2006). In the present study, the participants tended to select high-frequency characters for writing to dictation. This may explain why the syllable frequency and homophone density effect on the reaction times were negligible when the character frequency of written characters was considered in Model 2.

The most critical finding of this study is the facilitative O-to-P consistency effect on the reaction time; suggesting that it takes less time to produce a character with higher O-to-P consistency. Previous studies have demonstrated the O-to-P consistency effect, which caused the participants to take more time to process low O-to-P consistency characters than high O-to-P consistency characters on visual word recognition (Chang, Hsu, Tsai, Chen, & Lee, 2016; Lee et al., 2004, 2005). Our finding of the O-to-P consistency effect on auditory recognition supports the existence of the second-order O-to-P consistency effect on Chinese writing to dictation. That is, when an auditory word activated its orthographic representations, the activation was spread to its orthographic neighbors (other characters sharing the same phonetic radical). If all or most of these orthographic neighbors share the same pronunciation (high O-to-P consistency), the selected characters receive stronger support from these neighbors and thus facilitate the writing-to-dictation process.

Congruent with previous studies (Davies & Weekes, 2005; Leung et al., 2013; Stone & Van Orden, 1997), the second-order mapping consistency effect in either visual or spoken word recognition seemed to be affected by the first-order mapping consistency. However, the present study did not find an interactive effect between the O-to-P consistency and homophone density effect. We reasoned that both the latency and generation probability measures reflect the outcome of auditory word recognition. These indices may be too inaccurate for revealing the delicate relationship between the homophone density and O-to-P consistency. Therefore, Experiment 2 was conducted to orthogonally manipulate both the homophone density and O-to-P consistency with the ERP technique to investigate when and how the O-to-P consistency and homophone density influence the processes of Chinese writing to dictation.

3. Experiment 2: ERP study

The ERP technique involves measuring the temporal dynamics of brain responses at a millisecond scale and provides a set of ERP components, such as N1, P2, N400, and the LPC, for indexing different stages of lexical processing. Recent studies have applied ERPs to track the temporal loci of the orthographic effects on spoken word recognition in various tasks (Pattamadilok, Perre, Dufau, & Ziegler, 2009; Perre, Pattamadilok, Montant, & Ziegler, 2009b; Perre & Ziegler, 2008). For example, Perre and Ziegler (2008) manipulated the orthographic consistency at the first or second syllable of spoken words in an auditory lexical decision task. They found that inconsistent words evoked larger central-posterior distributed negativities than consistent words did from 300 to 350 ms and extended to around 600 ms that time-locked to the onset of inconsistency in spoken words. By using the semantic go/no-go task, Pattamadilok et al. (2009) also demonstrated orthographic consistency effects that emerged early from 300 to 350 ms and late from 400 to 700 ms over frontal to central regions More importantly, these effects occurred before the onset of word frequency effects, a temporal marker for lexical access, suggesting that orthographic knowledge is activated automatically and sufficiently early to affect the core processes of lexical access during auditory word recognition.

Only a few studies have used ERPs to investigate orthographic effects on Chinese spoken word recognition (Chen et al., 2016; Wang et al., 2012). Wang et al. (2012) investigated the homophone density effect of Chinese monosyllables on N400 in an auditory lexical decision task. They found that high homophone density words elicited greater negative potentials between 600 and 800 ms, over the frontal-central region, than low homophone density words did. They suggested that the greater negativity reflected the competition among multiple semantic codes associated with the homophones. Chen et al. (2016) used ERPs to differentiate the homophone density and orthographic consistency in Chinese spoken monosyllable word processing in a semantic categorical task. The orthographic consistency effect was found at N400 (450–650 ms) with frontal-central distribution, whereas the homophone density effect occurred in the LPC (700–900 ms) with central parietal distribution. A larger N400 for high orthographic consistency words indicated more orthographic neighbors at the radical level compared with low orthographic consistency words, whereas a larger LPC for low homophone density words were recognised more easily and retrieved without competition between homophones compared with high homophone density words. Overall, these results support the orthographic influence on Chinese spoken word recognition. However, it remains unclear whether the second-order O-to-P consistency effect can be consistently found during Chinese spoken word recognition.

The results of Experiment 1 provided a data set of Chinese monosyllabic words and the generation probabilities of the written characters that the participants produced when hearing Mandarin monosyllabic words. With this database, in Experiment 2, the homophone density of monosyllabic spoken words and the O-to-P consistency of their corresponding characters with the highest generation probability were manipulated. Using ERPs enables identifying the temporal locus of homophone density and O-to-P consistency effects and to investigate how these effects interact with each other in Chinese writing to dictation.

3.1. Methods

3.1.1. Participants

Twenty-four right-handed college students (12 male, aged 20–28 y, mean 23 y) participated in Experiment 2. All the participants were native-Chinese speakers with normal or corrected-to-normal vision and hearing, and with no neurological or psychiatric diseases. Informed written consent was received from all the participants.

3.1.2. Experimental design

This study used 108 monosyllabic Chinese spoken words from the database of Experiment 1. For all the stimuli, the generation probability of the corresponding written characters had to be higher than 60% (mean 85.5%, SD = 11.9%, ranging from 60.9% to 100%). These spoken words were first divided into two conditions based on their homophone density (HD, high vs. low). Syllables with low homophone density have no homophones (HD = 1), whereas those with high homophone density have at least three homophones (HD ≥3). Under the high homophone density conditions, according to the O-to-P consistency (O−P) of the highest generation probability of a corresponding character, the syllables were classified to the high or low O-to-P consistent condition. Orthographic neighbors sharing the same phonetic radical for high O-to-P consistent characters are pronounced the same way (the index of O−P > 0.7), whereas those for low O-to-P consistent characters are pronounced in multiple ways (the index of O−P < 0.4). Examples of the four conditions are described as follows: (1) low HD/high O−P (mean of HD = 1, SD = 1; mean of O−P = 0.96, SD = 0.08); the syllable *yuǎn* maps onto 遠 only, and its orthographic neighbors 園, 轅, and, 猿 which contain the same phonetic radical 袁 are pronounced *yuán*; (2) low HD/low O−P (mean of HD = 1, SD = 1; mean of O−P = 0.18, SD = 0.085); the syllable *duǎn* maps onto 短 only, and its orthographic neighbors as [豆,逗,荳], [豎], and [頭], which contain the same phonetic radical 豆, are pronounced *dòu*, *shù*, and *tóu*, respectively; (3) high HD/high O−P (mean of HD = 6.04, SD = 2.07; mean of O−P = 0.81, SD = 0.28); the syllable *cǎi* can map onto 彩, 採, 踩, 綵, 睬, and 采; and their orthographic neighbors 彩, 採, 踩, 綵, 睬, 采, and 菜, which contain the same phonetic radical 采, are pronounced *cǎi*; and (4) high HD/low O−P (mean of HD = 4.70, SD = 1.85; mean of O−P = 0.32, SD = 0.26); the syllable *cāng* can map onto 倉, 滄, 蒼, and 艙; and their orthographic neighbors [槍, 鎗, 嗆, 搶, 蹌], [倉, 滄, 蒼, 艙], and [創, 瘡, 愴], which contain the same phonetic radical 倉, are pronounced *qiāng*, *cāng*, and *chuàng*, respectively. Under the high homophone density conditions, at least two characters had high character frequency among a set of homophones (≥500/per million). All the spoken words with a 70-dB female voice at approximately 650 ms were recorded through Adobe Audition®.

3.1.3. Procedures

The participants sat at an approximate distance of 75 cm from "eye to monitor," stared horizontally at the center of the monitor, and were tested individually in a soundproof room. The sounds were presented binaurally through speakers beside the monitor. The participants underwent 15 practice trials and 3 sessions (36 randomized experimental trials per session). The participants were allowed to take a break between test sessions for as long as they needed. The trials were begun with a fixed cross appearing on the central screen for 500 ms, and then the participants heard a 650-ms target word while the fixed cross remained on the screen for 1500 ms. While hearing the target word, the participants were asked to wait for an arrow sign to appear on the screen and then write the first character that came to mind on a tablet with a pen (Wacom Bamboo Pen CTL-470). The interval between the sound and the appearance of the arrow sign was 850 ms. The sequences of strokes were recorded and presented on the screen while the participants produced written responses. After finishing writing, the participants clicked right on the mouse with the left index finger; a capital "B" then appeared in the center of the screen for 1500 ms. The screen then turned blank for 500 ms before the start of the next trial. The participants were then asked not to blink while the fixed cross remained on the screen, but to blink quickly while writing or when a capital "B" appeared during the trials.

3.1.4. Electroencephalogram recording and preprocessing

Electroencephalogram (EEG) signals were continuously recorded using 64 Ag/AgCl active electrodes in accordance with an internal 10–20 system embedded in an elastic cap (QuickCap, Neuromedical Supplies, Sterling, USA). A common vertex reference was placed between Cz and CPz, and a ground electrode was affixed to the forehead anterior to Fz. Two electrodes (M1 & M2) were placed on the left and right mastoids for further rereferenced analysis. Additional electrodes were used to record electrooculogram signals and were placed at the outer canthi (HEOR & HEOL for horizontal eye movement) and supra- and infraorbital ridges of the left eye (VEOU & VEOD for vertical eye movement). The electrode impedances were maintained at approximately 5 kΩ and sampled at a 1000-Hz rate.

The EEG data were rereferenced offline to the average of the left and right mastoids with Compumedics Neuroscan 4.5 software and were preprocessed with FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011). The EEG data were segmented into epochs that were time-locked to the onset of the target word from −100 to 1000 ms. Eye movement artifacts identified in independent component analysis were removed from all segmented trials, and trials with amplitudes larger than ± 70 μV were removed. The segmented trials with correct responses, in which the properties of orthographic outputs matched the design of each condition, were computed in ensemble empirical mode decomposition (EEMD) analysis (Wu & Huang, 2009).

3.1.5. EEMD decomposition

EEMD analysis, an advanced version of empirical mode decomposition (EMD) (N. E. Huang et al., 1998), is a data-driven method for analyzing nonlinear and nonstationary signals and decomposing waveforms into a set of intrinsic mode functions (IMFs) with oscillatory modes (Huang et al., 1998). IMFs can present the local properties of events in time and frequency. Several studies have demonstrated that the application of EMD or EEMD for ERP data analysis may provide better estimates of ERP latency and amplitude, increase the effect size, and improve the signal-to-noise ratio and statistical power (Al-Subari et al., 2015; Cong et al., 2009; Hsu, Lee, & Liang, 2016; Kuo, Lin, Dressel, & Chiu, 2011; Lee, Chang, Hsieh, Deng, & Sun, 2012; Williams, Nasuto, & Saddy, 2011; Wu et al., 2012).

The current study used the EEMD procedure described by Hsu et al. (2016) and Chen et al. (2016) to analyze the EEG data without baseline correction and band-pass filtering. First, Gaussian white noise at 10% amplitude of the EEG signal's standard deviation was added to a signal of each EEG trial of each channel. An EMD algorithm was then applied to decompose the noise-added signal into

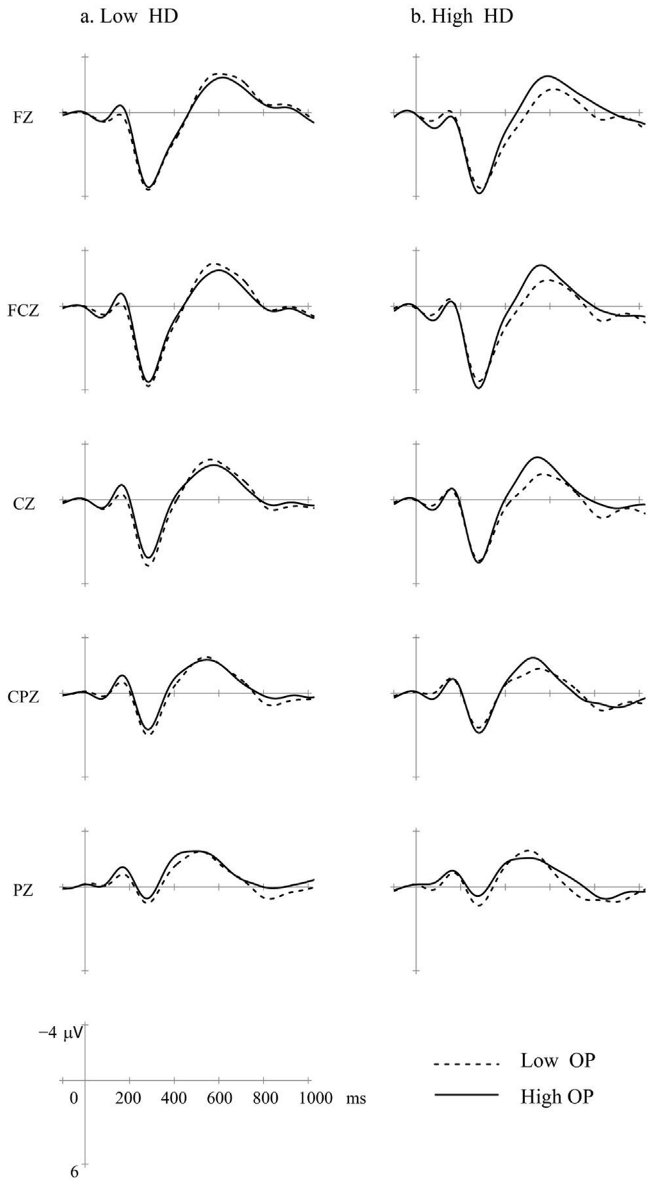

Fig. 1. ERMs for high O-to-P consistency characters (high OP, solid lines) and low O-to-P consistency characters (low OP, dashed lines) at the represented electrodes under (a) low homophone density (low HD) and (b) high homophone density (high HD) conditions.

nine IMFs and one residual trend. These steps were repeated many times with different white noises to obtain 40 ensembles of corresponding IMFs. The resultant IMFs were obtained by averaging all ensembles of each IMF, and their time-frequency spectra were evaluated using Hilbert spectrum analysis. The results revealed that IMF 5 showed a central frequency at 9.05 Hz, ranging from 3 to 15 Hz; IMF 6 showed a central frequency at 3.52 Hz, ranging from 1 to 7 Hz; IMF 7 showed a central frequency at 2.01 Hz, ranging from 0.5 to 4 Hz; and IMF 8 showed a central frequency at 1.51 Hz, ranging from 0.5 to 3 Hz.

Based on Chen et al. (2016), the current study performed a summation across IMF 6, IMF 7, and IMF 8 to cover the frequencies distributed between 0.5 and 7 Hz were summed and then averaged across all trials for each condition at each electrode to provide event-related modes (ERMs) for constructing the original ERPs (Al-Subari et al., 2015).

3.1.6. LMM analyses for mean amplitudes

Fig. 1 shows the grand averaged ERMs of the four conditions at the representative electrodes. Visual inspection of the data revealed the typical N100 and P200 components in the auditory paradigm, followed by the N400 from 450 to 650 ms and the late positive component (LPC) from 700 to 900 ms. As suggested by Chen et al. (2016), this study examined the homophone density and O-to-P consistency effects and how these effects interact with each other by comparing the mean amplitudes on P200 (245–295 ms), N400 (450–650 ms) and the LPC (700–900 ms). The differences between the mean amplitudes for the four conditions in the three

Table 4
Means and standard deviations of the accuracy (%) of written responses in each condition.

Homophone density	O-to-P consistency	
	High	Low
Low	85 (10)	81 (14)
High	85 (7)	88 (7)

temporal windows of interest were calculated by LMMs over each region of interest (ROI). Five ROIs were defined as follows: frontal (F3, F1, FZ, F2, F4), frontal-central (FC3, FC1, FCZ, FC2, FC4), central (C3, C1, CZ, C2, C4), central-parietal (CP3, CP1, CPZ, CP2, CP4), and parietal (P3, P1, PZ, P2, P4). The LMMs were estimated by including the participants as a crossed random effect, as well as the homophone density (high/low), O-to-P consistency (high/low), and interaction between the homophone density and O-to-P consistency as fixed effects. The estimated coefficient (β), standard error (*SE*), and *t* value for fixed effects are listed in Table 6. Fixed effects exhibiting $|t|s > 2$ were considered significant (Baayen, 2008).

3.2. Results

3.2.1. Behavioral results

The accuracy of written responses was analyzed by applying LMM analysis with the participants as a crossed random effect (Tables 4 and 5). The fixed factors included the homophone density (high/low), O-to-P consistency (high/low), and interaction between the homophone density and O-to-P consistency. The result showed a significant interaction between the homophone density and O-to-P consistency ($\beta = 0.074$, $SE = 0.029$, $t = 2.565$). The O-to-P consistency effects revealed opposite patterns under both high and low homophone density conditions. Under the low homophone density condition, the high O-to-P consistency characters showed higher accuracy (85% ± 10, *mean* ± *SD*) than the low O-to-P consistency characters did (81% ± 14). As for high homophone density words, the low O-to-P consistency characters exhibited higher accuracy (88% ± 7) than the high O-to-P consistency characters did (85% ± 7). Furthermore, the results showed a significant main effect of homophone density ($\beta = 0.039$, $SE = 0.014$, $t = 2.672$), although the main effect of O-to-P consistency was not significant ($\beta = -0.045$, $SE = 0.014$, $t = -0.321$). The characters with high homophone density demonstrated higher accuracy (86% ± 11) than those with low homophone density did (83% ± 12).

The generation probability of each written response was analyzed by applying the LMM analysis with the syllable as a crossed random effect (Table 5). The fixed factors included the homophone density (high/low), O-to-P consistency (high/low), and interaction between the homophone density and O-to-P consistency (HD:OP). The results showed a significant main effect of homophone density ($\beta = -0.663$, $SE = 0.140$, $t = -4.720$), whereas the main effect of O-to-P consistency ($\beta = -0.220$, $SE = 0.156$, $t = -1.408$) and the interaction effect between homophone density and O-to-P consistency ($\beta = 0.177$, $SE = 0.090$, $t = 1.966$) were not significant. The characters with high homophone density demonstrated lower generation probability than those with low homophone density did.

3.2.2. Electrophysiological results

Table 6 reports the results of LMM analyses for the homophone density effect, O-to-P consistency effect, and interaction between these effects (HD:OP) on P200, N400, and the LPC in five ROIs.

The LMM analyses of P200 showed neither the main effects of homophone density and O-to-P consistency nor the interaction effect between the homophone density and O-to-P consistency were significant in all the ROIs (all $|t|s < 2$).

The LMM analyses of N400 showed significant interactions between the homophone density and O-to-P consistency in frontal-central ($\beta = 1.3090$, $SE = 0.5389$, $t = 2.429$) and central ($\beta = 1.1265$, $SE = 0.5251$, $t = 2.145$) ROIs, and a significant main effect of homophone density in the parietal ROI ($\beta = 0.5356$, $SE = 0.2570$, $t = 2.084$). As presented in Fig. 1, under the high homophone density condition, characters with a high O-to-P consistency elicited more negative N400 than those with a low O-to-P consistency did. However, no significant main effects of the O-to-P consistency were consistently found in any of the ROIs (all $|t|s < 2$).

Table 5
Linear mixed model estimates of the fixed effects for (A) accuracy and (B) generation probability in the ERP study.

	(A) Accuracy			(B) Generation probability		
Variables	Beta	Std.Error	*t*-value	Beta	Std.Error	*t*-value
(Intercept)	0.846	0.015	55.906	1.553	0.245	6.327
HD	0.039	0.014	2.672*	−0.663	0.140	−4.720*
OP	−0.004	0.014	−0.321	−0.220	0.156	−1.408
HD*OP	0.074	0.028	2.565*	0.177	0.090	1.966

*Significant at $|t| > 2$.

Table 6
Linear mixed model estimates of fixed effects for the average amplitudes in P200 (245–295 ms), N400 (450–650 ms) and the LPC (700–900 ms).

		245–295 ms			450–650 ms			700–900 ms		
ROIs	Variables	Beta	Std.Error	*t*-value	Beta	Std.Error	*t*-value	Beta	Std.Error	*t*-value
Frontal	(Intercept)	5.1012	0.4914	10.382	−1.6563	0.3428	−4.832	−0.5811	0.3223	−1.803
	HD	0.0315	0.3037	0.104	0.5041	0.2831	1.781	0.4940	0.2774	1.781
	OP	−0.0700	0.3037	−0.231	0.4064	0.2831	1.436	0.2595	0.2774	0.936
	HD*OP	−0.5054	0.6074	−0.832	1.1243	.5661	1.986	0.8273	0.5548	1.491
Frontal-central	(Intercept)	4.8660	0.5211	9.338	−2.0814	0.3260	−6.385	−0.1490	0.3346	−0.445
	HD	−0.014	0.2915	−0.048	0.3260	0.2694	1.210	0.2926	0.2865	1.021
	OP	−0.0550	0.2915	−0.188	0.2860	0.2694	1.061	0.2114	0.2865	0.738
	HD*OP	−0.5231	0.5829	−0.897	1.3090	0.5389	2.429*	0.7126	0.5731	1.243
Central	(Intercept)	3.6512	0.5254	6.949	−2.1263	0.3294	−6.455	0.2190	0.3354	0.653
	HD	−0.0558	0.2784	−0.201	0.3016	0.2625	1.149	0.2038	0.2605	0.782
	OP	−0.0900	0.2784	−0.322	0.1744	0.2625	0.664	0.2125	0.2605	0.816
	HD*OP	−0.8123	0.5568	−1.459	1.1265	0.5251	2.145*	0.2094	0.5210	0.402
Central-parietal	(Intercept)	2.0937	0.4794	4.367	−1.7618	0.3309	−5.324	0.5839	0.3218	1.814
	HD	−0.1203	0.2398	−0.502	0.3781	0.2605	1.452	0.3000	0.2598	1.154
	OP	−0.0659	0.2398	−0.275	0.1208	0.2605	0.464	0.1261	0.2598	0.485
	HD*OP	−0.7167	0.4796	−1.494	0.7593	0.5210	1.457	−0.0099	0.5196	−0.019
Parietal	(Intercept)	0.6391	0.3962	1.613	−1.5108	0.3014	−5.013	0.6401	0.2452	2.610
	HD	0.1476	0.2410	0.612	0.5356	0.2570	2.084*	0.5262	0.2435	2.161*
	OP	−0.1824	0.2410	−0.757	0.1142	0.2570	0.444	0.0821	0.2435	0.337
	HD*OP	−0.7636	0.4820	−1.584	0.1697	0.5140	0.330	−0.4945	0.4870	−1.015

*Significant at $|t| > 2$.

The LMM analyses of the LPC yielded a significant main effect of homophone density in the parietal ROI ($\beta = 0.5262$, $SE = 0.2435$, $t = 2.161$), in which the high homophone density words elicited a greater LPC than the low homophone density words did (Fig. 2). However, there were no significant main effect of the O-to-P consistency or interaction between the homophone density and O-to-P consistency in any of the ROIs (all $|t|\text{s} < 2$).

3.3. Discussion

The present study examined the homphone density effect and the O-to-P consistency effect on Chinese writing to dictation. The ERP data revealed that the O-to-P consistency effect interacts with the homophone density effect in the N400 time window with frontal-central distributions, and a homophone density main effect in the LPC in the parietal regions. These findings support that when orthographic information is activated, it sends the feedback activation to phonology during Chinese spoken word recognition.

First, in the P200 time window, our data did not show any significant effect for the homophone density or O-to-P consistency. Previous ERP evidence suggests that the O-to-P consistency effect on P200 in reading Chinese affects early sublexical phonological computation (Hsu, Tsai, Lee, & Tzeng, 2009; Lee et al., 2006, 2007). However, the O-to-P consistency on spoken word recognition is consdered a second-order loop, because it appears after the conversion from phonology to orthograpgy. Because most studies on spoken word recognition have reported P-to-O consistency effects emerging from 300 to 350 ms and extending to around 600 ms (Chen et al., 2016; Pattamadilok et al., 2009; Perre, Pattamadilok, et al., 2009b; Perre & Ziegler, 2008), the absence of the second-order O-to-P consistency effect on spoken word recognition in the P200 time window seems reasonable.

Our results showed a significant interaction between the homophone density and O-to-P consistency on N400 with frontal-central distribution. High O-to-P consistency words elicited a more negative N400 response than low O-to-P consistency words did, and this was true only for the high homophone density condition. The larger N400 for high O-to-P consistent words than that for low O-to-P consistent words is congruent with the finding of Hsu et al. (2009). Hsu et al. (2009) reported that the O-to-P consistency effect on N400 may result from lexical competition within a phonological family, especially for phonograms with high combinability and large phonological neighborhoods. The orthographic neighborhood effect has also been demonstrated in previous studies, suggesting that words with larger orthographic neighborhoods elicit a larger N400 (Holcomb, Grainger, & O'Rourke, 2002; Huang et al., 2006; Laszlo & Federmeier, 2009; Müller, Duñabeitia, & Carreiras, 2010; Midgley, Holcomb, & Grainger, 2009; Vergara-Martínez & Swaab, 2012). Carrasco-Ortiz, Midgley, Grainger, and Holcomb (2017) investigated the effects of phonological and orthographic neighborhood sizes in lexical decision and semantic categorization tasks. They found that words with larger phonological neighborhoods elicited a greater N400 than did the small ones. Therefore, amplitudes of N400 increased with the increased neighborhood size. In the current study, the homophone density is defined as a set of homophones that share the same phonetic radical and therefore are orthographic neighbors. Our results imply that high homophone density words have more orthographic neighbors, and that high O-to-P consistent words have more phonological neighbors. The overall numbers of neighbors within the bidirectional mapping at the sublexical level

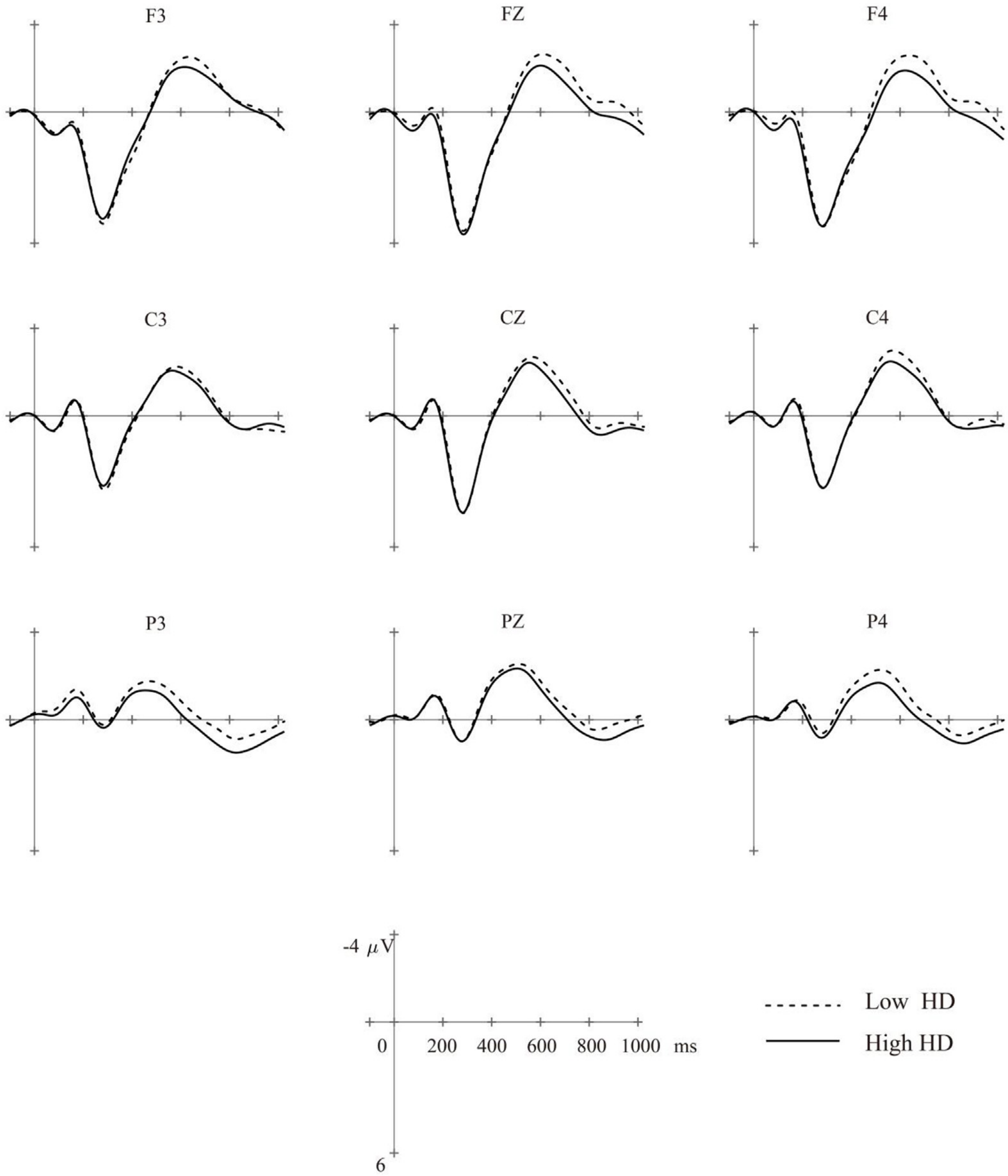

Fig. 2. ERMs for the high homophone density condition (high HD, solid lines) and low homophone density condition (low HD, dashed lines) at the represented electrodes.

elicited greater N400s.

Another result is that the homophone density effect was found in the LPC in parietal regions. High homophone density words elicited larger positivity than low homophone density words did. Previous studies have found the LPC following N400 during visual (Bakker, Takashima, van Hell, Janzen, & McQueen, 2015; Holcomb et al., 2002; Kwon, Nam, & Lee, 2012) and auditory word recognition (Chen et al., 2016; Hunter, 2016; Perre, Midgley, & Ziegler, 2009a). These studies have suggested that compared with an N400 that reflects an automatic retrieval of semantic representations (Kutas & Federmeier, 2011), the LPC is linked to controlled and effortful semantic processing (Hoshino & Thierry, 2012; Juottonen, Revonsuo, & Lang, 1996; Martin, Dering, Thomas, & Thierry, 2009; Rohaut et al., 2015; van Gaal et al., 2014). The LPC effect on semantic retrieval and integration has been observed in the attended language (Hoshino & Thierry, 2012; Martin et al., 2009), the unmasked condition word (van Gaal et al., 2014), and in patients without impaired consciousness (Rohaut et al., 2015). Kwon et al. (2012) reported that words with a larger morphological family elicited greater LPCs than did those with a small morphological family, and suggested that the LPC is associated with the semantic richness of a word. Moreover, the LPC has been associated with successful recollection in recognition memory (Rugg & Curran, 2007). A larger LPC was associated with the process of items that require recollecting greater amounts of information (Vilberg, Moosavi, & Rugg, 2006; Vilberg & Rugg, 2009) or items with higher response accuracy for sucessfull recollection (Murray, Howie, & Donaldson, 2015). Chen et al. (2016) reported that low homophone density words elicited a greater LPC than did high homophone density words in a semantic categorization task. They thus determined that high homophone density words encounter greater competition in semantic selection than low homophone density words do. Therefore, the greater LPC elicited by low homophone density words implies its advantage in memory retrieval and decision making in semantic categorization. However, in the present writing to diciation task, the accuracy data from both the norming study (Experiment 1) and ERP study (Experiment 2) showed that the accuracy increased with the increased homophone density. That is, it was easier for the participants to produce characters correctly for spoken words with high homophone density. Therefore, in writing-to-dictation tasks, high homophone density words demonstrate an advantage in memory retrieval and thus elicit a greater LPC than low homophone density words do.

4. General discussion

This study aimed to investigate whether the second-order O-to-P consistency effect would play a role during Chinese spoken word recognition in the writing to dictation task. To setup the stage, we first collected a large sample of writing-to-dictation responses for 230 Chinese monosyllabic spoken words from 16 college students in Experiment 1, in order to estimate the generation probability of their corresponding written responses. Meanwhile, the LMM analyses nicely demonstrated the roles of syllable frequency, homophone density, O-to-P consistency, character frequency, and numbers of strokes in writing to dictation. To be more specifically, syllables with higher homophone density effects showed higher production accuracy. However, as there're more candidates for written responses, the generation probability of each candidate decreased and the overall reaction time increased, with the increased homophone density. Critically, there was a facilitative O-to-P consistency effect on the reaction time. This finding supports that, not only the first-order mapping consistency effect but also the second-order mapping consistency effect are evident on Chinese writing to dictation.

Experiment 2 conducted an ERP study to further investigate this issue by manipulating the homophone density of the spoken words and the O-to-P consistency for their written responses with the highest generation probability in the database that established in Experiment 1. The results of behavioral data replicated the facilitative homophone density effect on accuracy and the inhibitory homophone density effect on generation probability, which had been demonstrated in the norming study (Experiment 1). When hearing the spoken words with high homophone density, participants could have many orthographic candidates to write down, which decrease the rates of the null responses or writing errors. Due to different written responses produced among these participants for the same spoken words with high homophone density, it decreased the generation probability of each character corresponding the same syllable. Moreover, in our writing-to-dictation task, the participants were asked to write only one character for the corresponding monosyllabic spoken word. Thus, a longer reaction time is needed for participants to decide which character to be written down. Furthermore, the ERP results demonstrate an interactive effect between homophone density and O-to-P consistency on N400. The high O-to-P consistency words elicited the increased N400, especially for those with high homophone density. The results support a second-order O-to-P mapping consistency and how it interacts with the homophone density on Chinese spoken word recognition.

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