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Consistency and regularity effects in character identification: A greater role for global than local mapping congruence

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A B S T R A C T

Consistency and regularity, concepts that arise, respectively, from the connectionist and classical cognitive modeling work in alphabetic reading, are two ways to characterize the orthography-to-phonology mappings of written languages. These concepts have been applied to Chinese reading research despite important differences across writing systems, with mixed results concerning their relative importance. The present study of covert naming in Chinese is distinctive in testing the ERP effects of regularity and consistency in a fully orthogonal design. We found that consistency, but not regularity, affected the N170, P200 and N400 as well as pronunciation transcription accuracies, demonstrating a more prominent role of consistency than regularity in character naming, consistent with conclusions from English word naming. To capture a generalization across writing systems, we propose *mapping congruence* as a writing-system-independent way of referring to orthography-to-phonology mappings and illustrate these congruence effects in an interactive framework of character identification.

1. Introduction

The importance of phonology in word reading across writing systems raises the question of how a word's phonology is accessed during the rapid process of word identification. In reading alphabetic writing, two concepts, consistency and regularity, have been involved in answering this question. Consistency in English is measured by whether the spelling of a word's (spoken) rime unit (e.g., *-ade* of the word *wade*) is pronounced the same in all its orthographic neighbors (e.g., *wade*, *made*, *jade*, *lade*). Thus, *wade* is consistent because it rhymes with all its orthographic neighbors, whereas *wave* is inconsistent because *-ave* is pronounced differently in *have*. Orthographic neighbors (e.g., *have*) having a different pronunciation of (*-ave*) sometimes are called "enemies" of a word (e.g., *wave*); neighbors (e.g., *save*, *cave*, *wave*, *gave*) having the same pronunciation of (*-ave*) are "friends" (Jared, 1997; Taraban & McClelland, 1987). Consistent words are named faster than inconsistent words, producing a consistency effect (e.g., Glushko, 1979; Jared, McRae, & Seidenberg, 1990).

The regularity in English refers to whether the pronunciation of a letter or letter string in the word conforms to the Grapheme-Phoneme Correspondence (GPC) rules based on the most frequent letter-to-phoneme mapping across all word forms. For example, the English word *must* is regular because the letter <*u*> is pronounced as /ʌ/ according to the GPC rules; the word *deaf* is an exception word because the letter string <*ea*> is pronounced as /ɛ/ rather than /i/, which is the GPC rule for <*ea*> . Regular words are named faster than exception words, producing a regularity effect (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Seidenberg, Waters, Barnes, & Tanenhaus, 1984).

The demonstrated contributions of both regularity and consistency raise two questions we address here: What is the relative significance of each factor? Does the answer depend on properties of the writing system? These questions are important for general theories of word reading. This is because one factor (regularity) assumes the process of word reading isolates the word as a unique form whereas the other (consistency) assumes this process is influenced by properties of the written lexicon beyond the word being read. The effects of regularity and consistency have been addressed in alphabetic reading and more recently in Chinese, which presents an especially interesting comparison point, as we explain later. First, we briefly review the conclusions from studies of alphabetic reading.

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1.1. Consistency and regularity in English reading

Regularity is implemented in the Dual-Route Cascaded (DRC) model (Coltheart et al., 2001) using local word-based representations and GPC rules of written English. These rules assign a model pronunciation to a letter or letter string. A regular word allows a sublexical procedure to succeed in pronouncing the words according to the GPC rules. However, this sublexical procedure yields incorrect pronunciations for irregular or exception words, whose pronunciations depart from the GPC rules, producing a regularity effect in English reading (e.g., Seidenberg et al., 1984). The regularity effect is greater for low-frequency words than high-frequency words (e.g., Paap & Noel, 1991; Seidenberg et al., 1984), and greater when the irregularity occurs at an early letter position, decreasing monotonically over letter positions from left to right (Coltheart & Rastle, 1994).

In contrast, consistency arises from consideration of syllable rime units (Glushko, 1979) and has been prominent in connectionist approaches (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996) that assume no local word representations. Instead, orthography-phonology connections of various grain sizes (not only syllable rime units) are weights between distributed feature units as determined by prior learning of pronunciations of similarly spelled words, i.e., orthographic neighbors. Thus, pronunciation consistency of a letter pattern (e.g., *-ade*) across all of its occurrences determines the connection weights between feature units, producing a consistency effect in naming (e.g., Glushko, 1979).

However, the consistency effect (i.e., faster naming speed for consistent words), defined by dichotomous categories of consistent and inconsistent pronunciations as in Glushko, (1979), was not always replicated in subsequent studies (e.g., Andrews, 1982; Seidenberg et al., 1984). Later studies (e.g., Jared et al., 1990; Jared, 1997, 2002) increased the evidence for consistency effects by considering the degree of inconsistency in terms of the characteristics of a word's orthographic neighborhood, specifically its same-pronunciation "friends" and its different-pronunciation "enemies". Jared (2002) presented three types of low frequency English words: regular-consistent (e.g., *boom*), regular-inconsistent (e.g., *bead*), and exception-inconsistent (e.g., *pint*). Inconsistent words were further differentiated by the summed frequency of their friends and enemies, creating two categories: words high in the summed frequency of friends and low in the summed frequency of enemies (HFLE), and words low in the summed frequency of friends and high in the summed frequency of enemies (LFHE)[1]. Relative to matched words that were regular and perfectly consistent, the degree of inconsistency defined by these neighborhood characteristics affected naming performance, regardless of regularity, whose effect was restricted to inconsistent words with few friends (LFHE). These consistency effects were also observed in high frequency words (Jared, 1997). Jared (2002) concluded that consistency, as well as variation in the neighborhood characteristics that define it, are the dominant factors in English word naming, whereas regularity has a smaller, restricted contribution.

1.2. Consistency and regularity in Chinese reading

Written Chinese, a morpho-syllabic writing system, presents a sharp contrast to alphabetic writing. Its basic unit is the sinogram (i.e., Chinese character), a term that captures the uniquely Chinese origin and structural properties of Chinese characters (Wang & Tsai, 2011). A sinogram maps onto a single syllable that is usually also a morpheme. No element of a sinogram represents a phoneme, although sublexical constituents (radicals) can represent a syllable, a morpheme or both. Although simple characters have no radicals, 80 percent of sinograms are complex characters called phonograms (Zhou, 1978). These phonograms (e.g., 植*, /zhi*[2]*/, 'plant'*) combine a phonetic radical (直*, /zhi/, 'vertical'*) that can provide information about the pronunciation of the host character, with a semantic radical (木, */mu/, 'wood related'*) that can imply meanings of the host character. Some radicals (e.g., 直 and 木) can stand alone as legal characters themselves, and thus have their own pronunciations and meanings.

The orthography-to-phonology mappings of written Chinese can be characterized by consistency in a manner parallel to English. A consistent character (e.g., 浓, */nong/*) is homophonic (sharing the same syllable, ignoring tone differences) with all of its orthographic neighbors (e.g., 侬, 脓, 哝), i.e., those sharing the same phonetic radical (e.g., 农); an inconsistent character (e.g., 距, */ju/*) has at least one non-homophonic orthographic neighbor (e.g., 柜, */gui/*, sharing its phonetic radical 巨, */ju/*, Fang, Horng, & Tzeng, 1986; Hue, 1992; Lee et al., 2004). The degree of consistency can be quantified by either type or token counts (e.g., Hsu, Tsai, Lee, & Tzeng, 2009; Lee, Tsai, Su, Tzeng, & Hung, 2005). For example, the character 炬 (*/ju/*), with its character frequency of 12 per million, has a total of 5 orthographic neighbors (i.e., 距, 拒, 矩, 钜, 柜): 4 friends (i.e., 4 homophonic orthographic neighbors: 距, 拒, 矩, 钜, with their character frequencies of 98, 74, 16, and 1 per million, respectively), and 1 enemy (i.e., 1 non-homophonic orthographic neighbor: 柜, */gui/*, with its character frequency of 44 per million). Thus, the character 炬 has a type consistency value of $(1 + 4)/(1 + 5) = 0.83$ and a token consistency value of $(12 + 98 + 74 + 16 + 1)/(12 + 98 + 74 + 16 + 1 + 44) = 0.82$. The "enemy" character 柜 has a type consistency value of $1/(1 + 5) = 0.17$ and a token consistency value of $44/(12 + 98 + 74 + 16 + 1 + 44) = 0.18$. Thus, the token consistency value ranging from 0 to 1 is a quantity that captures both the dichotomous definition of consistency and the neighborhood characteristics that were defined in English research. Phonograms with high type and token consistency values (e.g., 炬) can be referred to as high-consistency characters, whereas characters with low type and token consistency values (e.g., 柜) can be referred to as low-consistency characters.

Through a tenuous analogy with English, the regularity of a character has been defined by the phonological relationship between the host character and its phonetic radical (e.g., Fang et al., 1986; Zhou & Marslen-Wilson, 1999). Phonograms having the same syllable pronunciation (ignoring tone) as their phonetic radicals were defined as regular characters, and the others as irregular characters (Fang et al., 1986; Lee et al., 2005; Yum, Law, Su, Lau, & Mo, 2014; for more stringent definitions, see Zhou & Marslen-Wilson, 1999). Thus, the phonogram 呱 (*/gua/*, *a sound*) is a *regular* character because it is pronounced identically with its phonetic radical 瓜 (*/gua/*, *'melon'*); the phonogram 钮 (*/niu/*, *'button'*) is an *irregular* character because it is pronounced differently from its phonetic radical 丑 (*/chou/*, *'ugly'*). Unlike in English where regularity applies to every word, regularity cannot be applied to all characters, but only to the subset of phonograms that contain a phonetic radical that can stand alone as a legal character. Indeed, one can argue that "regularity" fails to capture the way written Chinese provides pronunciation information (Perfetti, Zhang & Berent, 1992), an issue we return to in the discussion.

With these definitions of consistency and regularity, Chinese allows a factorial design with consistency and regularity orthogonally manipulated. The high-consistency character 炬 is regular because it is homophonic with its phonetic radical 巨; the irregular character 钮 is high-consistency because it is homophonic with most of its orthographic neighbors, 妞, 扭, 忸, 纽; the regular character 呱 is low-consistency, because it is pronounced differently from most of its orthographic neighbors, 孤, 弧, 狐; the low-consistency character 柜 is irregular, because it is pronounced differently from its phonetic radical 巨. In fact, in Chinese the set of words that is both irregular and perfectly consistent

[1] These neighborhood characteristics can be quantified by token consistency (i.e., the ratio of the summed token frequencies of friends to the summed token frequencies of both friends and enemies): HFLE words have a token consistency value > 0.5, whereas LFHE words have a token consistency value < 0.5.

[2] The letters represent the official Romanization of standard Chinese, Pinyin.

is very small, as in English (Glushko, 1979).

1.3. Consistency and regularity effects in Chinese reading

1.3.1. Behavioral studies

Early studies of sinogram naming found that regularity interacted with frequency (e.g., Exp 2 in Hue, 1992), as it does in English (Seidenberg et al., 1984), producing a regularity advantage specifically for low-frequency characters. These studies used three types of characters (regular-consistent, regular-inconsistent and irregular-inconsistent) and found consistency effects without regularity effects in low-frequency characters only (Fang et al., 1986; Exp 3 in Hue, 1992). However, neither Fang et al., (1986) nor Hue (1992) controlled neighborhood characteristics, i.e., the character frequencies of friends and enemies. Later research (Lee et al., 2005), following Jared (1997), considered these neighborhood characteristics, defined consistency as graded measures (i.e., type and token consistency values). Consistency effects were found in both high- and low-frequency characters, whereas a regularity effect was found in low- but not in high- frequency characters. Lee et al., (2005) argued that consistency was more important than regularity in reading sinograms because the consistency effects were not constrained by character frequency. Furthermore, consistency applies to all phonograms, whereas the regularity was restricted to phonograms that contain phonetic radicals that can stand alone as legal characters (See also Lee, 2008).

1.3.2. Event related potential (ERPs) studies

ERP components associated with the brief course of word identification can add informative data on these issues. For instance, the N170 has been interpreted as reflecting fast orthographic detection at the initial stage of perceptual categorization (e.g., Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Lin et al., 2011) and automatic activation of orthography-to-phonology mappings (e.g., Maurer & McCandliss, 2007). The P200 has been associated with early orthographic and phonological processing in both English (e.g., Kramer & Donchin, 1987) and Chinese (Kong, Zhang, Zhang, & Kang, 2012; Kong et al., 2010). The N400, well-known for its association with semantic processing (Kutas & Federmeier, 2011; Lau, Phillips, & Poeppel, 2008), may also reflect a more general congruence between stimuli, including phonological congruence of two successively presented words (e.g., the rhyming word pairs, *make* and *ache* in Rugg & Barrett, 1987). In Chinese, Liu et al., (2003) found the N400 is sensitive to phonological sameness (homophones) of successively presented characters during a meaning judgment task. Thus, ERPs can reveal the emergence of *ortho*-phonological effect (consistency and regularity) at different time points, indexed by the N170, P200 and N400.

So far, ERP research on Chinese reading shows mixed results for consistency and regularity. Consistency effects have been found in covert naming tasks (e.g., pronunciation judgments; Hsu et al., 2009; Lee et al., 2007). Lee et al., (2007) found that when participants judged whether a target was homophonic with a probe character, inconsistent characters elicited greater N170, greater P200 and smaller N400 than consistent characters. In addition, the N170 response was modulated by phonetic combinability (i.e., the number of orthographic neighbors containing the same phonetic radical) for high-consistency characters (Hsu et al., 2009). However, a more recent ERP study (Yum et al., 2014) emphasized the role of regularity over consistency, showing early and lingering regularity effects on N170, P200 and N400 in contrast to a relatively transient consistency effect observed on only the P200 with more positive amplitude for consistent than inconsistent characters. Yum et al., (2014) stressed the role of regularity because it showed effects comparable to the consistency effects reported in Hsu et al., (2009) and argued that the consistency effects in Hsu et al., (2009) and Lee et al., (2007) were likely confounded with regularity. Indeed, none of these ERP studies on consistency effects has reported the regularity of characters.

To summarize, previous research has produced mixed results on the relative role of consistency and regularity in Chinese reading. Behavioral studies comparing three types of characters (regular-consistent, regular-inconsistent, and irregular-inconsistent) have supported a dominant role for consistency (e.g., Fang et al., 1986; Hue, 1992; Lee et al., 2005). ERP studies show mixed results. Those finding consistency effects (Hsu et al., 2009; Lee et al., 2007) did not report controls for regularity. The study by Yum et al., (2014) examined both consistency and regularity, but did so through separate experiments that varied one factor while controlling for the other. This approach allowed additional uncontrolled factors, including the range of word frequency and the number of character stimuli across the two sets of materials.

We address these issues with an ERP study that provides the first full factorial design test of consistency and regularity in native Mandarin speakers with a complete single set of sinograms.

1.4. The present study

Using ERPs, we test consistency and regularity effects in a single set of characters with a complete orthogonal design that creates sets of irregular high-consistency and irregular low-consistency characters; these sets have been collapsed generally into a single set of irregular inconsistent characters in previous Chinese reading research. We use an implicit naming task that presented two characters sequentially for a same-different pronunciation judgment. Participants were instructed to name covertly the first character, the critical character for ERP recording. Consistency and regularity were orthogonally manipulated among these critical characters, which were of low frequency in a range where both consistency and regularity effects are readily observed. After the ERP experiment, participants did a pronunciation transcription task, writing each character in Pinyin to assess their knowledge of the pronunciations.

We tested two contrasting hypotheses regarding the relative roles of consistency and regularity in Chinese reading. One is that consistency, because it reflects the rapid influence of a character's *ortho*-phonological neighborhood, would emerge in the early stages of *ortho*-phonological processing of character reading and thus affect the N170, P200 and N400. The contrasting hypothesis is that, because regularity reflects the *ortho*-phonological influence from a character's phonetic radical, regularity would modulate these early ERP components. A third possibility is that consistency and regularity contribute jointly to character identification during naming, a possibility not discoverable with the previously used non-orthogonal designs. The behavioral results of interest are in the Pinyin transcription task, where we expect consistency and regularity effects in transcription accuracy. Such effects are not expected in the same-different pronunciation judgment task, because the judgments were made on the (second) probe character; the first character's sublexical structure should be irrelevant by that time, 1600 ms after the onset of the first character.

2. Materials and methods

2.1. Participants

Thirty-six undergraduate students (16 males; *Mean* age = 19, *SD* = 1.2, range 18–22) at the University of Pittsburgh participated in the ERP experiments. All participants grew up in Mainland China, and were right-handed, native Mandarin speakers with normal or corrected-to-normal vision. Written informed consent was obtained from all participants, with all procedures approved by the University of Pittsburgh Institutional Review Board.

2.2. Materials

The critical characters, which were always presented first, were 184 low-frequency (below 40 per million) characters, each in one of the four conditions defined by the orthogonal manipulation of consistency (high vs. low) and regularity (regular vs. irregular). Most characters in each condition (37–45 of 46 total) have left–right configuration (e.g., 炬) with some top-down configuration (e.g., 窃) and very few semi-closure (e.g., 迭) or closure configurations (e.g., 囤). Samples of the 46 characters in each condition are shown in Table 1. High-consistency characters (including perfectly consistent characters) had their type and token consistency values significantly higher than low-consistency characters. All regular characters shared their syllable with their phonetic radicals (ignoring tone), whereas irregular characters had a pronunciation different from their phonetic radical. The four conditions of critical characters were matched in character frequency, number of strokes, phonetic combinability (all no less than 4), homophone density, semantic concreteness and radical token frequency (Table 1). In addition, each critical character was paired with two types of probe characters, which were always presented after the first (critical) character. The probes were either a homophonic probe character (a '*yes*' response), or a non-homophonic probe character, (a '*no*' response). The homophone probe character was usually the highest frequency within the set of characters that were homophonic with the critical character. This ensured that participants knew the pronunciations of these probe characters, which had been confirmed by our pilot experiments. The non-homophone probe characters were matched with homophone probe characters in terms of word frequency, character configuration and visual complexity.

2.3. Procedure

Each trial started with a fixation cross displayed for 300 ms, followed by the critical character for 800 ms. After an 800 ms blank interval, the probe character appeared and remained on the screen until a response. The inter-trial interval was 1800–2200 ms. Both characters were displayed in Song font, black against a gray background, at the center of the screen. Participants were seated 60 cm from the screen (visual angle: 1.9) in a dark shielded booth. Participants were instructed to silently name the first (critical) character in their mind and, when the second (probe) character appeared, to judge whether the two characters had the same pronunciation by pressing the appropriate yes or no key ('*D*' or '*K*', counterbalanced across participants). After the ERP experiment, participants were asked to transcribe the pronunciations of randomized critical characters in Pinyin, including both the syllables and tones. Participants were told to not guess but to leave the response area blank, if they did not know the pronunciation of the character.

The 46 critical characters in each condition were randomly assigned to two separate lists so that half of the stimuli (23) in each condition were followed by homophonic ('*yes*') probes and the other half (23) by non-homophonic ('*no*') probes. Each critical initial character appeared once for each participant and the probe types were counterbalanced across participants. All critical trials (184 with 1/2 homophone trials) were randomized and presented in six trial blocks, each beginning with two unmeasured warm-up trials. The first five blocks consisted of 32 critical trials (8 for each condition) and the final block 24 critical trials (6 for each condition).

2.4. Electroencephalogram (EEG) recording and preprocessing

A 128 electrode Geodesic sensor net with Ag/AgCI electrodes (Electrical Geodesics, Inc., Eugene, OR) recorded EEGs at a sampling rate of 1000 Hz with impedances kept below 40 kΩ.

2.5. Data analyses

Accuracy of the pronunciation transcription task that followed the ERP experiment identified characters as either known or unknown for each participant. Unknown characters included characters that were either transcribed incorrectly or marked as unknown. These accuracies were analyzed with Mixed-Effect Logistic Regression (MELR) using maximum likelihood estimation implemented in R. For the same-different pronunciation judgments, accuracies were also analyzed with MELR. Decision times, recorded from the appearance of the probe character, were analyzed with Linear Mixed-Effect Regression for those known characters that were identified correctly in the transcription task. All models included random effects of both subjects and items. The final model was obtained by using the likelihood-ratio test in comparing a model with fixed effects of regularity, consistency and their interaction, with nested simple models.

The EEG data were recomputed offline with EEGLAB in MATLAB, band-passed at 0.05–30 Hz, and re-referenced to the average of all channels. ERPs were computed for correct trials after ocular artifact rejection. Data of five participants showed excessive artifact rejection (leaving 17 or fewer trials per condition) and were not used in the data analysis. For each participant, unknown items were excluded from EEG data. Thus, the analysis was based on 31 participants, who obtained an average of 30 trials per condition after removal of excluded trials. Recording epochs were 1100 ms, including a 100 ms baseline prior to critical character onset. A global field power analysis (Skrandies, 2005) confirmed that voltage shifts occurred in the time windows we identified for testing the early and mid-latency components (100–150 ms, 170–260 ms, 300–450 ms) and, additionally in the late time window (500–800 ms) of the Late Positive Component (LPC). Thus, mean amplitudes in each of these time windows were tested for *ortho*-phonological effects on the N170, P200, N400 and LPC. These means were analyzed in a four-way ANOVA: regularity (regular vs. irregular), consistency (high vs. low), laterality (left, midline, right), and region as within-subject factors. The planned testing regions were as follows: the N170 at parietal (P3/Pz/P4) and occipital (O1/Oz/O2), the P200 at frontal (F3/Fz/F4), central (C3/Cz/4), and parietal (P2/Pz/P4) regions, the frontal N400 (FN400) at frontal regions, the central-parietal N400 at central and parietal regions, and LPC at frontal, central and parietal regions. Greenhouse-Geisser correction was applied to all repeated-measures with more than one degree of freedom.

3. Results

3.1. Pronunciation transcription task

On average, high-consistency critical characters ($M = 90\%$) obtained higher (+8%) accuracy than low-consistency ($M = 82\%$) characters (for details, see supplementary materials). The final model (Table 2a) showed that consistency had a significant effect on the logits of correctly transcribing characters after the variances associated with subjects and items were simultaneously controlled. Although regular characters showed higher (+3%) accuracy than irregular characters; neither the effect of regularity ($p > .1$) nor its interaction of consistency was significant. Unknown items, i.e., characters that were transcribed incorrectly or marked as unknown, were excluded in both behavioral and ERP data.

3.2. Same-different pronunciation judgement task

Participants obtained high accuracy ($M = 95\%$) in the same-different pronunciation judgement task. Responses to homophone trials (mean

Table 1
Sample stimuli: the four types of critical characters and their paired probe characters.

Critical character conditions					
Consistency		High-consistency		Low-consistency	
Regularity		Regular	Irregular	Regular	Irregular
Sample character		炬 */ju/* *'torch'*	钮 */niu/* *'button'*	呱 */gua/* *a sound*	赎 */shu/* *'redemption'*
Frequency (per million)		7.8 (7.2)	9.4(9.5)	9.4(9.8)	8.8(8.7)
Range: [min, max]		[0.5, 27.2]	[0.6, 30.5]	[0.4, 38.0]	[0.5,35.4]
Token consistency		0.8 (0.1)	0.8 (0.2)	0.1 (0.1)	0.1 (0.1)
Type consistency		0.6 (0.2)	0.6 (0.2)	0.2 (0.1)	0.2 (0.1)
Visual complexity		10.3 (3.0)	11.0 (3.5)	10.0 (2.6)	10.8 (2.8)
Phonetic combinability		7.5 (3.2)	6.5 (2.7)	7.7 (3.5)	7.4 (3.2)
Homophone density		17.2 (7.6)	15.6 (8.3)	17.0 (9.2)	15.6 (9.1)
Semantic concreteness		4.6(1.1)	4.7 (1.2)	4.4 (1.1)	4.5 (1.3)
Phonetic radicals		巨	丑	瓜	卖
token frequency (per million)		673.5 (958.4)	674.1(1128.3)	661.2 (1427.7)	619.6 (1283.4)
Range: [min, max]		[0.9, 4702.9]	[3.1, 6315.5]	[2.1, 8895.8]	[2.6, 8159.0]
Probe character conditions	**Homophone**	具 */ju/* *'tool'*	牛 */niu/* *'cow'*	剐 */gua/* *'cut''*	熟 */shu/* *'ripe'*
	Non-homophones	众 */zhong/* *'numerous'*	币 */bi/* *'currency'*	振 */zhen/* *'shake'*	暴 */bao/* *'violent'*

Note: All stimuli were chosen from a word frequency database from the Centre for Chinese Linguistics at Peking University and all psycholinguistic variables, including consistency values, were calculated on the basis of 5200 characters by the authors. The table shows the mean value and standard deviation (in the bracket) for each psycholinguistic variable. Homophone density refers to the number of the character's homophones across the whole lexicon. The semantic concreteness was rated by 32 undergraduate students, who did not participate in the ERP experiment and rated the concreteness of 324 characters on a 7-point Likert scale (1 representing abstract and 7 representing concrete), under the same instruction as Barca, Burani, & Arduino, (2002). Radical token frequency refers to the token frequency of radicals when standing alone as legal characters.

accuracy: 91%, mean decision times: 808 ms) were significantly (Table 2b and 2c) faster (–22 ms) but less accurate (-8%) than to non-homophone trials (mean accuracy: 98%, mean decision times: 830 ms); no other effects were observed. (For details, see supplementary materials.) ERP results recorded during the presentation of the first character are of primary interest and are reported below for each targeted ERP component.

3.2.1. *N170[3] (100–150 ms)*

Consistency significantly affected the N170 (for ANOVA, see Table 2d). High-consistency characters elicited a less negative (+0.297 μV) N170 than low-consistency characters (Fig. 1) in posterior areas. However, the effect of regularity was non-significant: Although regularity interacted with laterality, further analyses showed that the effect of regularity was not significant in the left hemisphere, midline area, or right hemisphere (all $ps > 0.1$).

3.2.2. *P200 (170–260 ms)*

Consistency interacted with laterality in the P200 (Table 2d): High-consistency characters elicited a more positive P200 than low-consistency characters (Fig. 1) in the midline ($p < .025$) and left hemisphere ($p < .05$) areas, but not in the right hemisphere ($p > .1$). No effect of regularity was observed ($ps > 0.1$).

3.2.3. *Central-parietal N400 (300–450 ms)*

Consistency significantly affected the N400 (Table 2d). High-consistency characters elicited a less negative N400 than low-consistency characters (Fig. 1) in the midline (+0.46 μV, $p < .001$) and the left hemisphere (+0.49 μV, $p < .001$), but not in the right hemisphere ($p > .1$). No effect of regularity was observed.

In addition to the planned analyses on the N170, P200 and N400 above, we carried out exploratory analyses on Frontal N400 (FN400) and LPC components following a comprehensive ANOVA and a global field power analysis[4] indicated different impacts of consistency and regularity across regions within the N400 and LPC time windows. These results are reported in the following section.

3.2.4. *Frontal N400 (FN400: 300–450 ms)*

Consistency interacted with regularity and laterality in modulating the FN400 (Table 2d). High-consistency characters elicited a more negative FN400 than low-consistency characters (Fig. 2). This difference (–0.58 μV) was significant (F4: $p < .001$) only for regular characters. Similarly, regular characters produced more negative FN400 than irregular characters (–0.69 μV), significant (F4: $p < .001$) for high-consistency characters only.

3.2.5. *Late positive complex (LPC: 500–800 ms)*

Consistency interacted with regularity and laterality in the LPC (Table 2d): High-consistency characters elicited more positive (+0.535 μV) LPC than low-consistency characters, significant at the left hemisphere ($p < .05$) for regular characters only (Fig. 2). However, neither the main effect of regularity nor the interaction of regularity and laterality was significant in either high- or low-consistency characters.

[3] We found that applying different re-referencing channels lead to effects of reversed polarity for early components in posterior regions (for more discussion, see Nieuwland, 2019): When re-referenced with the averaged mastoid, the grand ERPs in posterior clusters showed a N1 and P2 (see supplementary S3); When re-referenced with the global (all-channel) average (the default processing setting in EGI system), the grand ERPs in posterior clusters showed a P1-N2 complex (Fig. 1). Because N170 is associated with *ortho*-phonological processes, we refer to this complex as N170.

[4] Global field power analysis identified the time window of LPC and N400; a comprehensive four-way ANOVA of the N400 time window revealed that frontal regions (FN400) and typical central-parietal regions (N400) were affected differently by consistency and regularity, producing a significant three-way interaction of regularity, consistency and regions.

Table 2
Statistical results of behavioral and ERP data.

a. The final mixed-effect model for accuracy of the pronunciation transcription task
Logit of correct transcription ~ 1 + Regularity + Consistency + (1|Subject) + (1|Item)

Predictor	Coefficient	SE	Wald Z	p value
Intercept	2.96	0.19	15.23	**<.001**
Regularity	−0.41	0.32	−1.27	.2
Consistency	0.82	0.32	2.57	**<.05**

b. Accuracies of same-different pronunciation judgement task
Correct judgement ~ 1 + Regularity + Consistency + Probe type + (1|Subject) + (1|Item)

Predictor	Coefficient	SE	Wald Z	p value
Intercept	3.64	0.16	23.28	**<.001**
Regularity	−0.29	0.20	−1.43	.15
Consistency	0.19	0.20	0.92	.36
Probe type	2.02	0.17	11.74	**<.001**

c. Decision times of same-different pronunciation judgement task
Decision times ~ 1 + Regularity + Consistency + Probe type + (1|Subject) + (1|Item)

Predictor	Coefficient	SE	t	p value
Intercept	827.73	33.41	24.78	**<.001**
Regularity	3.70	11.89	0.31	.76
Consistency	0.97	11.90	0.08	.93
Probe type	20.73	6.94	2.99	**<.05**

d. Results of four-way repeated measure ANOVA for all ERP components

N170	**consistency**: $F(1, 30) = 7.38$, $MSE = 2.22$, $p < .05$ **regularity × laterality:** $F(1.60, 47.92) = 4.82$, $MSE = 0.50$, $p < .05$ (regularity effect: midline, $p > .1$, left hemisphere, $p > .1$, right hemisphere, $p > .1$)
P200	**consistency × laterality:** $F(1.53, 45.97) = 4.96$, $MSE = 0.88$, $p < .05$ (consistency effect: midline, $p < .025$, left hemisphere, $p < .05$, right hemisphere, $p > .1$)
N400	consistency: $F(1, 30) = 11.46$, $MSE = 1.51$, $p < .05$ **consistency × laterality:** $F(1.34, 40.20) = 8.67$, $MSE = 0.93$, $p < .05$ (consistency effect: midline, $p < .001$, left hemisphere, $p < .001$, right hemisphere, $p > .1$)
FN400	consistency × regularity: $F(1, 30) = 8.82$, $MSE = 1.88$, $p < .05$ **consistency × regularity × laterality:** $F(1.82, 54.60) = 5.34$, $MSE = 0.36$, $p < .05$
LPC	consistency × laterality: $F(1.63, 48.80) = 6.53$, $MSE = 1.00$, $p < .05$ **consistency × regularity × laterality:** $F(1.72, 51.54) = 4.74$, $MSE = 1.20$, $p < .05$

4. Discussion

We examined the relative contributions of consistency and regularity in sinogram naming by manipulating the two factors orthogonally. Behaviorally, consistency, but not regularity, affected the accuracy of the pronunciation transcription task. The ERP results showed consistency effects during the covert naming of characters across the N170, P200, and N400 windows where we expected to observe *ortho*-phonological effects. In addition to these targeted components, we found effects in the FN400 and the LPC. These results suggest that the phonological consistency of a character's orthographic neighborhood plays a continuous role from the earliest phases of orthographic identification, with a more restricted role for regularity.

An effect of regularity was not entirely absent. Regularity interacted with consistency in both the FN400 and the LPC: The FN400 showed a regularity effect only for high-consistency characters at Fz and F4 and a consistency effect at these clusters occurred only for regular characters. The greater LPC in the left hemisphere for high-consistency characters was also restricted to regular characters.

4.1. Consistency and regularity effects in character identification

Behaviorally, the pronunciation transcription task showed that participants' identification of character pronunciations was affected by consistency only, not regularity. High-consistency characters yielded higher accuracy (with fewer misidentifications and fewer marked as unknown) than low-consistency characters. This result suggests that the inconsistency of a character's neighborhood can result in more errors and uncertainties in generating pronunciations. Prior research with a non-orthogonal design and overt naming task (e.g., Lee et al., 2005) reported consistency effects in both high- and low-frequency characters (Exp 3), and regularity effect in low-frequency characters only (Exp 1). The results of our transcription task, however, found no regularity effect for our low-frequency characters.

The ERP data, time-locked to the critical characters in the pronunciation judgement task, showed early and continuous effects of consistency on the N170, P200 and N400, in contrast to the restricted regularity effect, which was found only on FN400 and LPC and only through an interaction with consistency. In the following, we discuss these effects on each component.

4.1.1. N170

High-consistency characters elicited a less negative N170 than low-consistency characters in posterior areas, consistent with Lee et al. (2007). However, different from Yum et al. (2014), the N170 showed no effect of regularity.

The reduced N170 for high-consistency characters may reflect stronger orthographic activation of the phonetic radical within a high-consistency character during the initial visual feature analysis stage, which arises from more feedback from the convergent phonology that occurs when many characters that contain the radical share its phonology (see also Section 4.2). The phonological mapping hypothesis (McCandliss & Noble, 2003) suggested that the N170 effect, which is usually left-lateralized in reading alphabetic languages, is related to the *ortho*-phonological connections that were established during learning to read; left-lateralization of the N170 effect to visual words should be less pronounced in Chinese (Maurer & McCandliss, 2007). Our finding of a bilateral N170 is consistent with this hypothesis.

We note that the N170 shift started at 100 ms, earlier than that typically reported in alphabetic studies (e.g., Hauk and Pulvermüller, 2004), but similar to some ERP studies of character reading (e.g., Xue, Maurer, Weng, & Zhao, 2019; Yum et al., 2014; Zhou, Fong, Minett, Peng, & Wang, 2014). In addition, Liu and Perfetti (2003) found that the differences of ERP waveforms between sinogram reading and English word reading for native Chinese readers with English as the second language started as early as 100 ms and peaked at around 150 ms (referred to as N150). If these apparent timing differences are real, rather than outcomes of particular studies that vary in numerous ways, writing system factors would be implicated.

4.1.2. P200

High-consistency characters elicited an enhanced (i.e., more positive) P200 than did low-consistency characters in the left hemisphere and midline areas, congruent with Yum et al., (2014), but not with Hsu et al., (2009) and Lee et al., (2007), who found a less positive P200 for high consistency characters that also extended to the N400.

The P200 has been associated with early orthographic (e.g., Kong et al., 2012; Liu et al., 2003; Zhang et al., 2020; Zou, Tsang, & Wu, 2019) and phonological (e.g., Kong et al., 2010) processing in Chinese as well as alphabetic reading (e.g., Kramer & Donchin, 1987). In Chinese, orthographic and phonological similarities can be manipulated independently. In studies in which two characters are judged for their meaning relatedness, similarity in orthography only (no similarity in phonology) and similarity in phonology only (no similarity in orthography) have produced P200 effects that are opposite in direction. In the independent manipulation of orthographic similarity, an initial character, 读, */du/*, '*read*', has the same radical as the critical character, 续, */xu/*, '*continue*') but different pronunciation and meaning. For such cases, Kong et al (2012) found a less positive P200 effect (see also Liu et al., 2003), which they interpreted as reflecting facilitated orthographic processing. In contrast, in the independent manipulation of

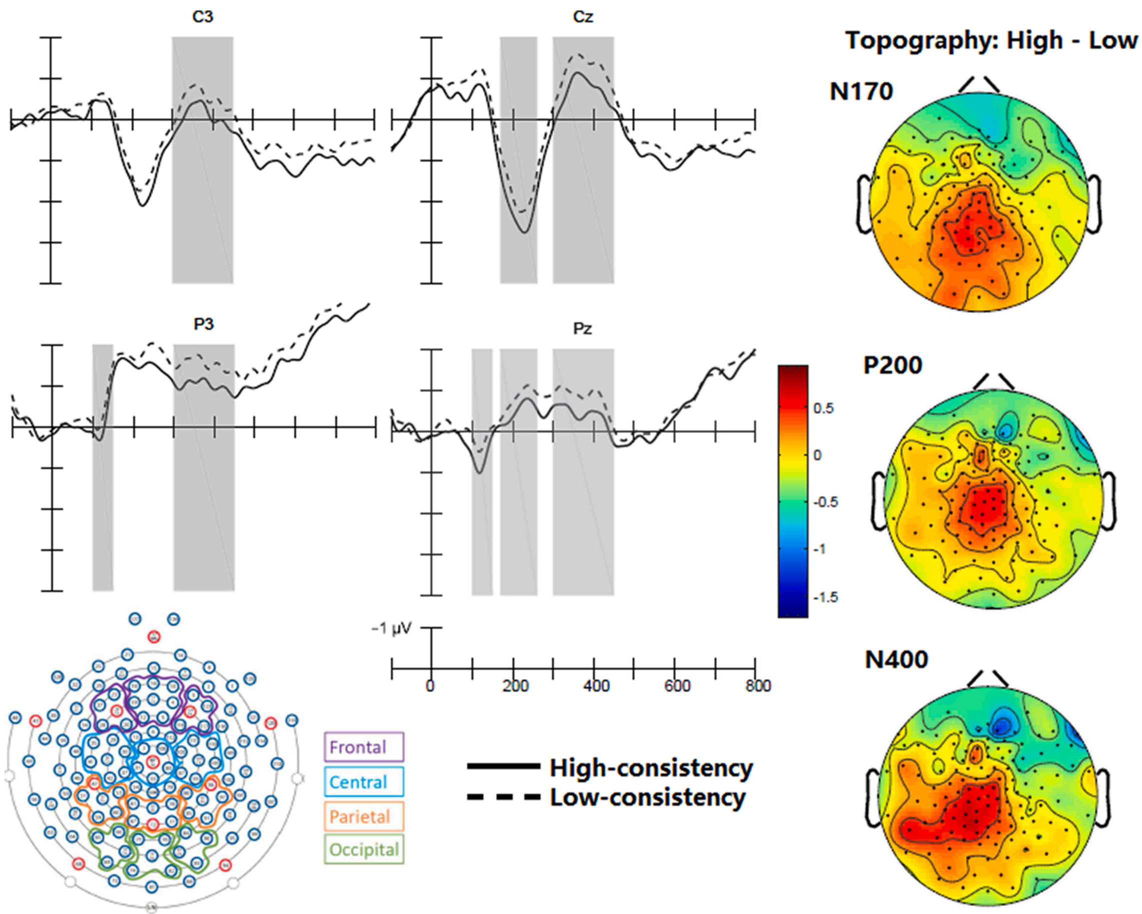

Fig. 1. Consistency effects on the N170, P200 and N400 components. *Notes:* 1. Grand average ERPs (negative up) on representative electrode clusters (i.e., C3, Cz, P3 and Pz) are shown on the left side. The highlighted (grey) part on ERP waveforms is the time window of each ERP component, where significant consistency effects on this electrode cluster were observed. 2. Topographic differences between high- and low-consistency characters in each ERP component are shown on the right side.

phonological similarity, the initial character, 雇, */gu/*, '*hire*' has the same pronunciation as the second critical character, 梏, */gu/*, '*manacle*', but the two have different radicals. Such cases have elicited an enhanced P200 effect (Kong et al., 2010; Zhang, Zhang, & Kong, 2009), interpreted as reflecting a facilitation of phonological processing.

Our results show a clear consistency effect where no initial character precedes and no judgments are required. This allows a clear interpretation of the activation of a single character for which the reader will generate phonology to prepare for a comparison. Thus, consistency here is an *ortho*-phonological effect: The enhanced P200 reflects stronger phonological activation of a high consistency character due to the high phonological congruence within the character's neighborhood; this positivity seems to extend to the N400, as described next.

4.1.3. N400

We found that high-consistency characters elicited a reduced (i.e., less negative) N400 compared with low-consistency characters in left hemisphere and midline, central-parietal areas. On one interpretation, the N400 reduction reflects facilitated activation of lexical information (Lau et al., 2008). In our task, this facilitated activation of lexical information (including orthographic, phonological and semantic) could be a consequence of the strong phonological activation produced by high-consistency characters. Consistent with this interpretation is the congruence account of the N400 as reflecting feature congruence across stimuli: phonological congruence (e.g., Liu et al., 2003) as well as semantic congruence (Brown & Hagoort, 1993) and congruence across nonlinguistic stimuli (e.g., words and pictures in Willems, Özyürek, & Hagoort, 2008). For example, in Chinese, the reduced N400 has been found in a semantic task when two characters without a meaning relation have phonological congruence, i.e., the same pronunciation (Liu et al, 2003). Thus, we suggest that the strong phonological congruence between the characters' high-consistency neighbors and the character itself is the source of the reduced N400.

Our study seems to be the first to find a reduced N400 effect of consistency, an effect localized in left hemisphere and midline, central-parietal areas. This result contrasts with the lack of a consistency effect by Yum et al., (2014), who instead found a consistency effect on the P200, as the present study also found. Our result contrasts in a different way with the reversed N400 effect (more negative for high consistency) reported in Hsu et al., (2009) and Lee et al., (2007), two studies by the same research group. The reason for these differences is not clear; however, it is worth noting that these opposite polarities for the consistency effect were also observed on the P200—more positive for high-consistency in our study and more negative in Hsu et al. (2009) and Lee et al. (2007). Although the procedures across all the studies were comparable, there appear to be differences in control of other stimulus variables—phonetic radical combinability, homophone density (feedback consistency), radical token frequency and semantic concreteness, all of which could affect early and mid-latency components. All these factors were controlled in the present study, whereas the others studies appear to have controlled some but not all of them.

4.1.4. FN400

Consistency interacted with regularity in modulating the FN400 amplitude. High-consistency characters produced a more negative FN400 than low-consistency characters in F4 electrode clusters in

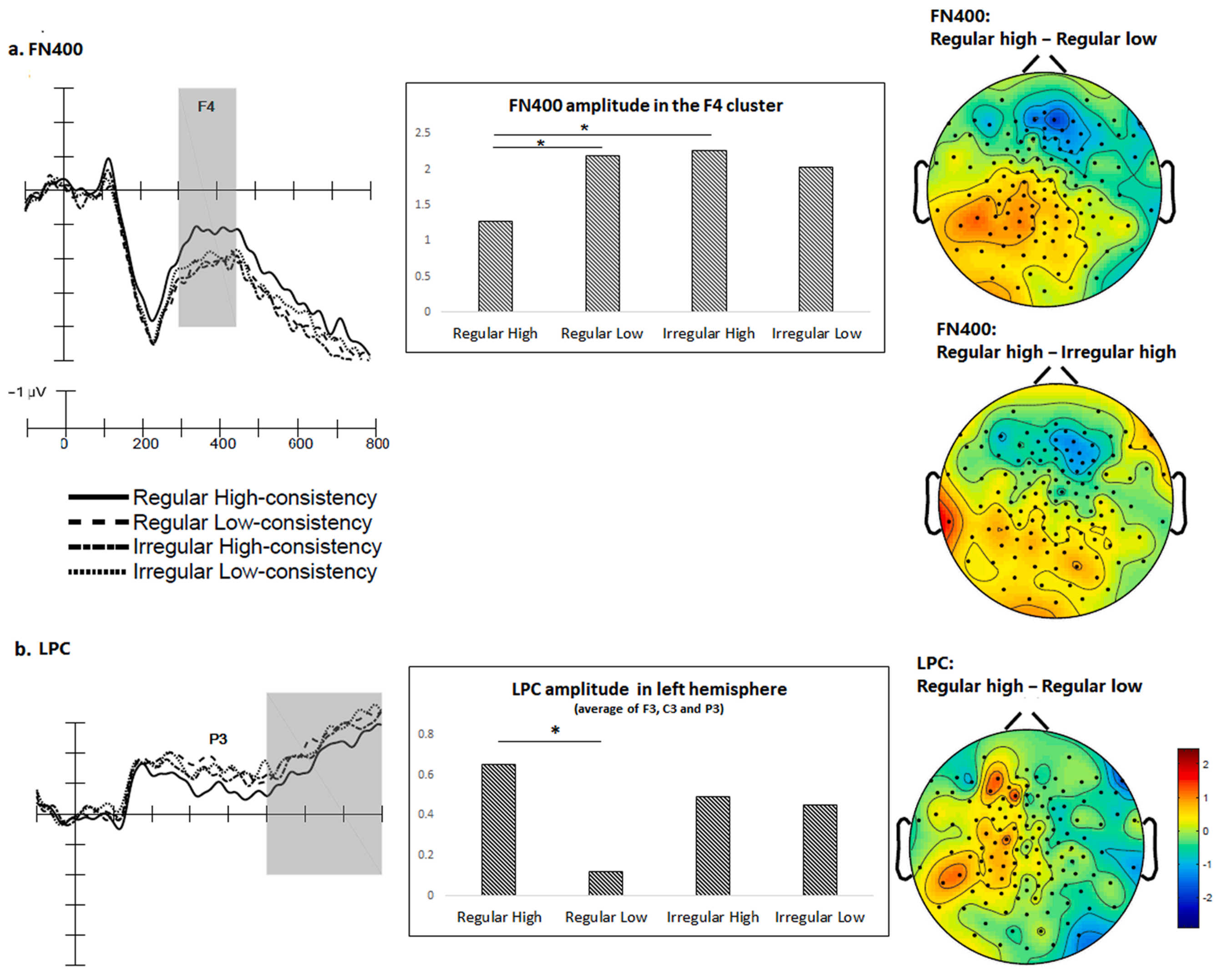

Fig. 2. Interactive effects of consistency and regularity on FN400 and LPC components.

regular characters only. Similarly, regular characters elicited more negative going FN400 than irregular characters in high-consistency characters only.

The FN400 has been associated with the processing of familiarity information in recognition memory research (e.g., Rugg & Curran, 2007) with more negative-going FN400 indicating less familiar. Although the assumption that the FN400 is functionally distinct from the parietal N400 has been questioned (Voss & Federmeier, 2011), additional studies have continued to find support for the FN400 as a familiarity-based recognition response (Bridger, Bader, Kriukova, Unger, & Mecklinger, 2012; Stróżak, Abedzadeh, & Curran, 2016).

On this interpretation, our results would suggest that regular characters of high-consistency were functioning as the least familiar characters, producing the most negative FN400. Our speculative account is that this reflects a character-specific familiarity that is reduced when lexical competition is high, as it would be in a neighborhood of regular high-consistency friends and its phonetic radical: A regular high-consistency character has its pronunciation associated with the largest number of characters, all sharing the same phonetic radical and the same pronunciation. The activation of many other (particularly high frequency) regular high-consistency neighbors, including the phonetic radical as a standalone character, provides a strong phonological signal while also interfering with the specific identification of the host character, making its unique orthographic form functionally “less familiar”.

4.1.5. LPC

Consistency also interacted with regularity in modulating the LPC amplitude. High-consistency characters elicited a more positive LPC in the left hemisphere than low-consistency characters in regular characters only. Again, no regularity effect was found.

The LPC has been associated with various interpretations across paradigms—episodic recollection during recognition memory (e.g., Rugg & Curran, 2007), updating working memory with information retrieved from long-term memory (e.g., Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991), conscious recollection of a prime-target relationship (e.g., Meade & Coch, 2017), and perceived recognition memory strength (Brezis, Bronfman, Yovel, & Goshen-Gottstein, 2017).

In our study, the more positive LPC for high-consistency characters suggest that the *global congruence* of the characters’ orthographic neighbors across the whole lexicon supports a strong memory for the critical character’s pronunciation, which, in our procedure, must be maintained in memory until the second character is presented. Moreover, the *local congruence* between the character and its phonetic radical adds to this effect of congruent phonology, creating a strong memory for the character’s pronunciation. This is consistent with the interpretation that the LPC in recognition memory can reflect perceived memory strength (Brezis et al., 2017).

4.2. The role of consistency and regularity in a character identification model

Models of character identification (e.g., Perfetti, Liu, & Tan, 2005; Taft, 2006; Zhou, Shu, Bi, & Shi, 1999; for review, see Reichle & Yu, 2018) generally have radicals as functional units. Such models allow a role for sublexical influences in character identification, but do not contain specific roles for regularity and consistency. To illustrate possible roles of consistency and regularity, we consider how a complex character and its phonetic radicals are represented in the orthographic system. This issue has been addressed in the model developed by Taft and colleagues (Taft, 2006) in a manner parallel with the interactive activation framework of alphabetic word reading (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). A complex character and its phonetic radical are represented in a hierarchical orthography subsystem (Fig. 3): the complex character at the lexical level and its phonetic radical at the sublexical level. The phonetic radical, which can stand alone as a character, has an additional representation at the lexical level that connects to its radical representation at the sublexical level. For example, the complex character 钮 (Fig. 3c) contains a phonetic radical 丑, which can stand alone as a character. Thus, 丑 has a lexical representation ('丑') that connects to its lexical pronunciation (*/chou/*), and a radical representation ('丑>') that connects to the complex character 钮 that contains it as a radical.

We use this model to illustrate consistency and regularity (Fig. 3). A high-consistency character (e.g., 炬, Fig. 3a) connects to the same phonological representation (*/ju/*) as four of its five orthographic neighbors (距, 拒, 钜, 矩). In contrast, a low-consistency character (e.g., 呱, Fig. 3b) connects to a pronunciation (*/gua/*) that is different from most of its orthographic neighbors (e.g., 弧, */hu/*, 孤, */gu/*, 狐, */hu/*). A regular character (e.g., 呱, Fig. 3b) has a phonological representation (*/gua/*) that connects to the lexical orthographic representation of its

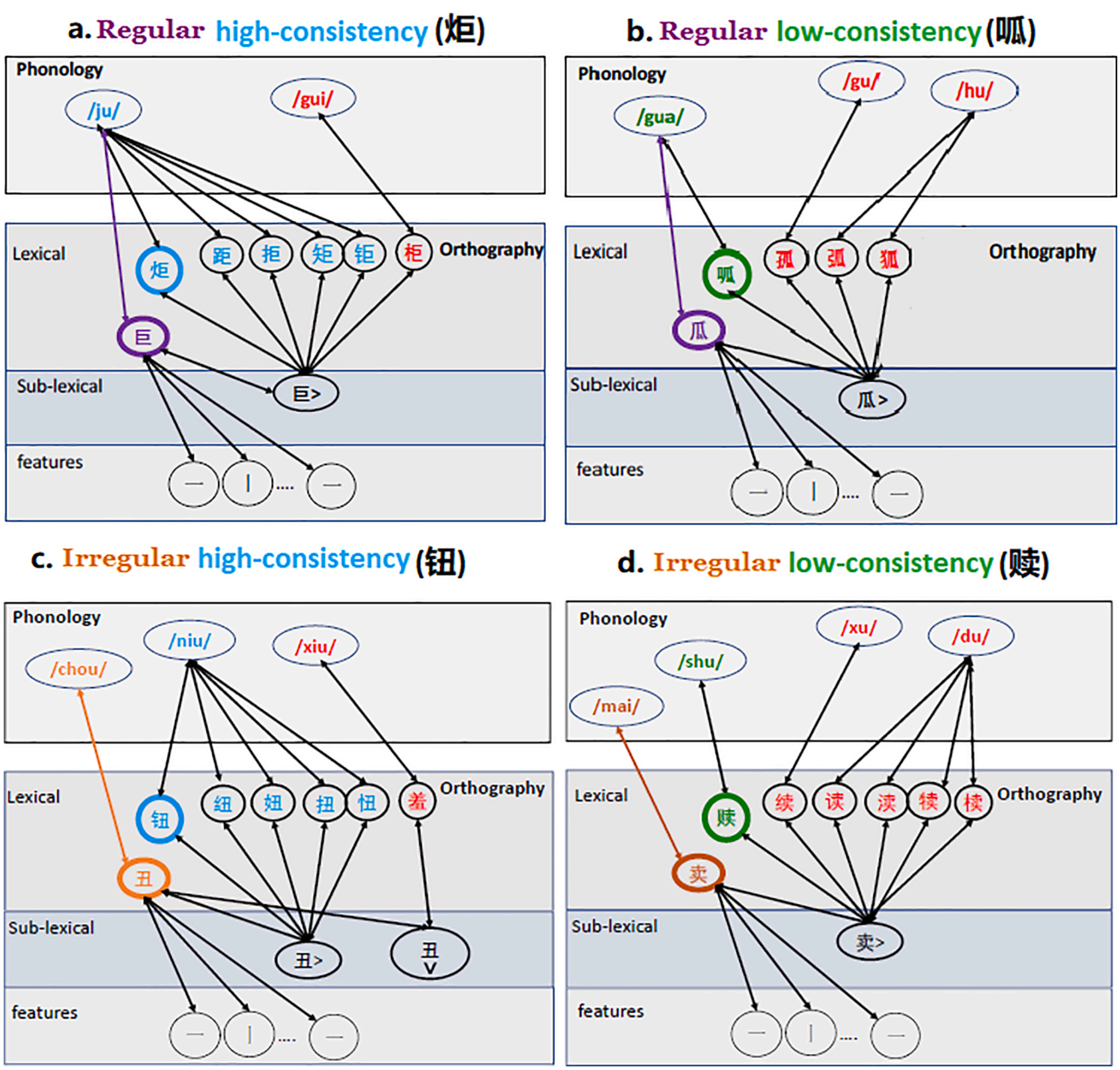

Fig. 3. Illustrations of consistency and regularity in Taft's model (Taft, 2006, the lemma subsystem and semantic subsystem are omitted to illustrate the orthography-to-phonology mappings): a. regular high consistency character (炬), b. regular low consistency character (呱), c. irregular high consistency character (钮), and d. irregular low consistency character (赎). *Notes*: 1. The symbol ">" around the radical representation indicates the position of radicals (e.g., '丑>' is the representation of the radical 丑 lying on the right side of the host characters). 2. High consistency characters (a and c) have most of their orthographic neighbors connecting to the same phonological representations; low consistency characters (b and d) have most of their orthographic neighbors connecting to different phonological representations; regular characters (a and b) have their phonetic radicals (purple) connect to the same phonological representations; irregular characters (c and d) have their phonetic radicals (orange) connect to different phonological representations.

phonetic radical (e.g., '瓜'). For an irregular character (e.g., 钮, Fig. 3c), its phonetic radical's lexical orthographic representation (e.g., '丑') connects to a different phonological representation (e.g., */chou/*). By the definition of orthographic neighbors (Fang et al., 1986; Lee et al., 2005), the lexical-level identity (e.g., the simple character 丑) of the phonetic radical (e.g., 丑) is not counted as an orthographic neighbor (e.g., 纽, 扭, 妞, 忸, 羞) of the host characters (e.g., 钮) that contain it. However, based on Taft's model, its lexical-level representation (e.g., '丑') may function as an additional "enemy" of an irregular host character (e.g., 钮); for a regular host character (e.g., 炬), its lexical-level representation (e.g., '巨') may function as an additional "friend". Thus, the lexical-level representation of the phonetic radical (e.g., '巨'), i.e., when it stands alone as a character, might be considered part of the lexical neighborhood that contains it as a radical (e.g., 炬, 距, 拒, 矩, 钜, 柜).

In this framework, the functionalities of consistency and regularity emerge from character-based and radical-based processes occurring in parallel (Fig. 3). This assumption is consistent with the spatial configuration of characters, which allows all components of a character to be viewed in a single fixation. Thus, the host character (e.g., 炬 in Fig. 3a) as a whole is processed and so is its phonetic radical, a constituent within the host character. The activation of the radical (e.g., '巨>') spreads to other characters in the host character's lexical neighborhood (e.g., 巨, 距, 拒, 矩, 钜, 柜) affecting support and competition from the character level. The activation of between levels is bi-directional, so that the radical's activation is affected also by the character's lexical neighborhood. These within-level and between-level effects combine to produce a resulting phonology of the host character. In this scenario, the phonetic radical of a high-consistency character, which has more orthographic neighbors that share the same pronunciation than does a low-consistency character, would be activated more strongly by convergent phonology (feedback) than the phonetic radical of a low-consistency character.

The consistency effect depends on the balance of support and competition a character (e.g., 炬) receives for its phonological representation from its orthographic neighborhood (e.g., 距, 拒, 矩, 钜, 柜). This balance could be determined by either type consistency (the number of friends relative to the total number of orthographic neighbors) or token consistency (the relative summed frequency of all friends relative to the summed frequencies of all orthographic neighbors). Considering type consistency, the phonology of a high-consistency character (Fig. 3a and 3c) benefits more by activation from a larger number of friends than a low-consistency character (Fig. 3b and 3d); by contrast, the phonology of a low-consistency character suffers from competition from a larger number of enemies than a high-consistency character. A token consistency effect arises similarly from the activation of the character's friends and enemies, but reflects a relative weighting based on the overall frequency of the friends relative to neighbors. Because the orthographic neighborhoods in our materials differed in consistency as defined by both token and type, we cannot make a conclusion on their relative importance.

The frequency of the host character may matter in two ways. First, character frequency affects the relative timing of the character-based and radical-based processes. In our materials, because the host characters are low frequency and their phonetic radicals have relatively higher token frequency, the radical-based process may initiate more rapidly to support or compete with its host character. Second, character frequency is part of the orthographic neighborhood effects, because the frequency of the host character relative to its friends/enemies affects the balance of support and competition the character receives from its neighborhood. In particular, whether a more frequent neighbor is a friend or enemy has a large effect on this balance. Because our host characters are low frequency, they are likely to have neighbors, either friends or enemies, of higher frequency.

Consistency effects, however, can appear even in high frequency characters when they have neighbors of higher frequency and thus receive additional support (or competition) from these higher frequency neighbors. Lee et al. (2005) compared consistency effects in overt naming task with (Exp 3) and without (Exp 1) considering the frequencies of a character's orthographic neighborhood. When the frequencies of orthographic neighborhood were considered (i.e., assessing the type and token frequencies of its friends and enemies as we did in this experiment), consistency effects were observed in both high and low frequency characters. (Still, the size of consistency effects was greater in low frequency than high frequency characters.) By contrast, when consistency was defined dichotomously (consistent vs. inconsistent) on the basis of type consistency without considering neighborhood (Exp 1), the consistency effect was observed in low frequency characters only (see also, Fang et al., 1986; Hue, 1992).

Regularity effects depend on phonological activation of the phonetic radical within the host character, supporting the phonological activation of regular characters (Fig. 3a and 3b), but creating phonological competition for irregular characters (Fig. 3c and 3d). The level of competition or support may be influenced by the frequency of the host character, its orthographic neighborhood, and the frequencies of the phonetic radical as a radical or a standalone character. However, regularity is defined as a property of a character, independent of its frequency and that of its phonetic radical. Any appeal to frequency-based explanations depends on neighborhood effects. The limited role of regularity relative to consistency in our result suggests that a model that considers the character in isolation from its orthographic neighborhood is not tenable.

4.3. Global vs local mapping congruence: A writing-system-independent account of the greater role of consistency over regularity across writing systems

To develop a generalized account of phonological processes across writing systems, we first consider the fundamental difference between regularity and consistency in Chinese. The consistency of sinograms reflects the extent of *global congruence* in the orthography-to-phonology mapping of a character in relation to its orthographic neighbors; in other words, consistency reflects the statistical distribution of orthography-to-phonology mappings across an orthographic lexicon of sinograms. By contrast, the regularity of sinograms reflects only the *local congruence* of a character's orthography-to-phonology mapping with that of its phonetic radical. The dominant role of consistency suggests that skilled readers learn the statistical distributions of orthography-to-phonology mappings over years of reading experience.

The use of "regularity" in Chinese is misleading as an analogy to alphabetic writing, where the idea of a "rule" implies a distinction between regular (rule-following) and irregular (rule-violating). Additionally, the way regularity supports alphabetic word identification, i.e., mapping speech units with lower level (non-morphemic) graphic units, does not apply to Chinese reading. Because of these differences, the use of "regularity" obscures structural properties that are involved in character identification and thus fails to be universal. The concept of validity rather than regularity may more accurately apply to Chinese: whether the phonetic radical is a valid cue to the pronunciation of the character (Perfetti et al., 1992; Zhang, Perfetti, & Yang, 1999). However, what is needed is a more universal description of orthographic structures, one that can apply to both nonalphabetic and alphabetic writing.

It is possible to capture the more universal aspects of orthography-to-phonology mappings in two dimensions that can apply across languages (Table 3). The first dimension is *global* versus *local,* which subsumes the distinction between consistency and regularity. Consistency reflects the global level congruence among a large set of orthographic neighbors across the entire lexicon; regularity reflects the local level congruence between a lexical unit and a single sublexical unit. The second dimension is *part* versus *whole*, which captures writing system differences in regularity and consistency. The sublexical-to-lexical mapping of Chinese is a *whole-to-whole* pronunciation mapping (i.e., from a syllable to a syllable for both regularity and consistency), whereas that of alphabetic

Table 3
Comparisons on consistency and "regularity" between Chinese and English.

	"Regularity" Local congruence	Consistency Global congruence
Part-to-Whole	English (**Phoneme-to-Syllable**)	English (**Rime-to-Syllable**)
Whole-to-Whole	Chinese (**Syllable-to-Syllable**)	Chinese (**Syllable-to-Syllable**)

Notes: 1. The units in the table are spoken language units that are mapped by graphic units. Thus, regularity in English depends on whether the "regular" phoneme for a given letter is compatible with the pronunciation of a given syllable. 2. These comparisons apply to only English monosyllabic words. English monosyllabic words have additional orthographic units that may be used (Taft, 1992).

writing is a *part-to-whole* mapping (e.g., from a phoneme (regularity) or a rime (consistency) to a syllable).

One might hesitate to consider regularity strictly local in English, because its sublexical units, as implemented in GPC rules, refer to the typical (i.e. most frequent across word types) pronunciation of a letter or letter string regardless of context. Thus, the local relationship of a grapheme to a given word is related to its statistical distribution in the lexicon. The GPC rules are "local" because they are "hardcoded" as local representations in the classical DRC model (Coltheart et al., 2001). In a more recent extended DRC model (Pritchard, Coltheart, Marinus, & Castles, 2016), a GPC rule-learning algorithm has been implemented to acquire the statistical distribution of orthography-to-phonology mappings. Thus, GPC rules have their computational properties derived globally, but they operate locally.

In this congruency-based reframing, consistency effects in Chinese and English are similar: Both reflect global level mapping congruence at the whole word (or morpheme) level. English global mapping, at least as implemented to date, uses the orthographic rime (also termed the orthographic "body", Taft, 1992) of the syllable for identifying the relevant neighborhood, whereas Chinese uses the orthographic syllable. (Rime units in English also are sometimes whole words, e.g. *ate* in *late, fate, mate*, etc.) Regularity differences, however, are potentially larger, because in English the relevant units generally do not have independent status as a morpheme. This framing accommodates the generalization implied by the present results and those of other research: Access to phonological information during reading is mainly affected by the global congruence of the written unit with the general orthographic lexicon rather than by its internal, local congruence.

Finally, we reconsider properties of the Chinese orthographic neighborhood that are important both for its measurement and for what counts as global congruence. We pointed out that a phonetic radical that can stand alone could be considered part of the lexical neighborhood that contains its host characters. The phonetic radical (e.g., 巨) would be a character in the lexical neighborhood (e.g., 巨, 距, 拒, 矩, 钜) of any complex characters (e.g., 炬) that contains it as a phonetic radical. Following the practice in other studies, however, we did not include the character-level of the radical in our measurement of the neighborhoods. The precise effects of including it depend on other factors and doing so generally would increase the contrast between high- and low-consistency characters. Nevertheless, our study found strong consistency effects without including the phonetic radical as a lexical neighbor.

Although it seems reasonable to add the radical as a character neighbor, there are counter considerations as well. The main one is that it is unclear to what extent the lexical identity of the simple character that corresponds to a phonetic radical (e.g., 巨) is comparable to the complex characters that constitute an orthographic neighborhood (e.g., 炬, 距, 拒, 矩, 钜). These complex characters contrast in form and function, containing multiple radicals that produce greater linguistic complexity and, with more strokes, greater visual complexity. Moreover, the frequency of the simple character as a radical and its frequency as a standalone character may affect its functioning at the sublexical level (Taft et al., 2000), perhaps by making complex character decomposition more likely and increasing radical-based processing in identifying these complex characters. A more general point, that applies also to alphabetic writing, is that orthographic neighborhoods, to the extent they are functional, may have internal structures. Complex characters in Chinese may be in different neighborhoods than simple characters just as polysyllabic English words may be in functionally different neighborhoods than monosyllabic words. The issue of the content of lexical neighborhoods is something to be addressed broadly across writing systems.

5. Conclusion

We examined the role of consistency (high vs. low) and regularity (regular vs. irregular) in sinogram naming with a 2-by-2 factorial design in which participants judged pronunciation sameness of two characters. The results show a greater role of phonological consistency, defined in relation to a character's orthographic neighborhood, than the regularity of a character, defined in relation to the congruence between the character and its phonetic radical. Behaviorally, high-consistency characters were transcribed more accurately than low-consistency characters in a pronunciation transcription task, in contrast with a null effect of regularity. Electrophysiologically, consistency played a continuous role during character identification of the covert naming task: High-consistency characters elicited less negative N170, more positive P200 and less negative N400 than low-consistency characters; by contrast, regularity affected FN400 and LPC only through an interaction with consistency. Although the use of "regularity" in Chinese is not an adequate analogy to alphabetic writing, our finding is consistent with the research of English word reading that demonstrated a dominant role of consistency over regularity. To better generalize across writing systems, we propose *mapping congruence* as a writing-system-independent way of referring to orthography-to-phonology associations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandl.2021.104997.

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