Consistency and regularity of Chinese characters: Global congruence plays a more important role than local congruence in character naming

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Submitted to the Graduate Faculty of the

Dietrich School of Arts and Sciences in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2020

UNIVERSITY OF PITTSBURGH

DIETRICH SCHOOL OF ARTS AND SCIENCES

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It was defended on

September 5, 2019

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University of Pittsburgh, 2020

The concepts of consistency and regularity characterize the orthography-to-phonology mappings of written languages. The use of these two concepts arises, respectively, from the connectionist and classical cognitive modeling work in reading alphabetic languages. Consistency has been argued to better characterize the difficulty associated with English word naming than regularity (Jared, 2002). Despite writing system difference, the concepts of consistency and regularity have been imported to Chinese reading in prior research. However, the issue of the relative contributions of each in Chinese character naming is still unclear. The current ERP study examines this issue by manipulating orthogonally the consistency and regularity of Chinese characters in a covert naming task. The results show that consistency, but not regularity, affects the N170, P200 and N400 responses during word recognition as well as the accuracies of transcribing character pronunciations during posttest questionnaires. In addition, consistency interacts with regularity in modulating the FN400 and LPC responses. These results demonstrate that consistency plays a more important role than regularity in character naming, in agreement with the conclusion in English word naming. We suggest that the two concepts can be reframed as mapping congruence that applies to two levels: Consistency reflects GLOBAL level (usually multiple units) congruence among orthographic neighbors across the whole lexicon; regularity reflects the LOCAL level (specifically two units) congruence between a lexical unit and a single

sublexical unit. Also, we illustrate their roles in an interactive framework of character recognition and discuss their impacts in this framework.

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Preface

This thesis is a final work as partial fulfillment for the degree of Master of Science in Department of Psychology, University of Pittsburgh. This work titled "Consistency and regularity of Chinese characters: Global congruence plays a more important role than local congruence in character naming" was carried out in the Perfetti Lab at University of Pittsburgh in 2018.

I would firstly like to thank my advisor, Dr. Charles Perfetti for all his help and guidance throughout the process of the thesis project. I would also like to thank my lab members, Lin Chen, Anne Helder, Xiaoping Fang, and Regina Calloway, and my friends in Pittsburgh, Qianru Yang, Xu Pan, Aria Wang, Ruizhe Liu, Brett Bankson and Jingyu Wu for their support and companion.

My sincere thanks also go to Dr. William S-Y. Wang and Dr. James W. Minett, who taught me and trained me in a Brain-Computer Interface (BCI) project in the language engineering lab at The Chinese University of Hong Kong, and led me into the field of brain and language research after my graduation from The Chinese University of Hong Kong.

Finally, my warmest thanks go to my parents, Zuwen Zhou and Dongjiao Peng, for their love and encouragement, without whom I would never have enjoyed so many opportunities.

I hope this thesis is useful for readers and for future research in Chinese reading as well as in cross-cultural reading research.

1.0 Introduction

The orthography-to-phonology mappings of written languages can be characterized by both consistency and regularity and both factors have been shown to affect the phonological processes of reading. Specifically, the consistency of an English word describes whether the letter pattern (e.g., -ADE) of a word (e.g., WADE) is pronounced consistently in all of the word's orthographic neighbors (e.g., WADE, MADE, JADE, LADE) that contain the same letter pattern. Thus, WADE is a consistent word because it rhymes with all its orthographic neighbors, whereas WAVE is inconsistent because its word body -AVE is pronounced differently from at least one orthographic neighbor, HAVE. Orthographic neighbors (e.g., HAVE) having a different pronunciation of the word body (-ADE) sometimes are called "enemies " of a word (e.g., WAVE), whereas neighbors (e.g., WADE, MADE, JADE, LADE) having the same pronunciation of the word body (-ADE) are "friends" of the word (e.g., WADE; Jared, 1997). Prior research shows that consistent words are named faster than inconsistent words, producing a consistency effect (e.g., Glushko, 1979).

In contrast to this description of consistency, the regularity of an English word refers to whether the pronunciation of a letter or letter string in the word conforms to the Grapheme-Phoneme Correspondence (GPC) rules . For example, the English word MUST is a regular word because the letter U is pronounced as /ʌ/ according to the GPC rules, whereas the word DEAF is an exception word because the letter string EA is pronounced as /ɛ/ rather than /i/ as the GPC rules predict. Prior research has shown that regular words are named faster than exception words, producing a regularity effect (e.g., Seidenberg, 1985). The demonstrated contributions of both regularity and consistency raise the question of the relative contribution of each.

The present study examines this question in reading Chinese, which presents a sharp contrast to alphabetic written languages in the mapping of orthography to the spoken language, as well as in its visual features. The concepts of consistency and regularity arise from the modeling work for reading alphabetic languages and especially for English reading because English has a great deal of inconsistency in the mapping of sub-lexical units to pronunciations. However, despite the fundamental writing system differences between English and Chinese, the ideas of consistency and regularity have been imported into Chinese research. The question of the relative contribution of consistency and regularity in English reading has been addressed conclusively (Jared, 2002); therefore, the answer to this question in Chinese reading has important implications for the modeling work toward a universal model of reading, which has sparked numerous discussions in reading research (e.g., Frost, 2012).

1.1 Consistency and regularity in English reading

Consistency and regularity are conceptualized and implemented by two different modeling approaches. Regularity is implemented in the Dual-Route Cascaded (DRC) model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) of reading, which assumes local word-based representations and GPC rules of written English. Regularity arises in describing whether a letter or letter string in a word conforms to these GPC rules, which provide a sublexical route to pronounce a word. Regularity plays a role by affecting the success and the speed of the sublexical route, as the regularity effect (e.g., Seidenberg, 1985) shows.

By contrast, consistency arises from the connectionist approach for reading, e.g., Parallel Distributed Processing (PDP) model (Plaut, McClelland, Seidenberg, & Patterson, 1996), which assumes no local representations for words' pronunciations. In addition, spelling-sound knowledge is represented by connection weights between spelling and sound feature units. These connection weights are determined by the knowledge of pronunciations of similar spelled words, i.e., orthographic neighbors, because they share the same spelling and sound feature units. Thus, consistency arises in describing whether the letter pattern (e.g., -ADE) of a word (e.g., WADE) is pronounced consistently among all the word's orthographic neighbors (e.g., WADE, MADE, JADE, LADE) containing the same letter pattern. Consistency plays a role by affecting the connection weights between shared feature units, as the consistency effect (e.g., Glushko, 1979) shows. .

In examining the relative contribution of consistency and regularity in English reading, Jared (2002) argued that consistency is the dominant factor in affecting naming performance, whereas regularity has only a small influence on English word naming. In particular, Jared (2002) examined the naming performance for three types of low-frequency English words (Experiment 1): regular-consistent, regular-inconsistent, and exception-inconsistent words. In addition, neighborhood properties of inconsistent words (including both regular- and exception-inconsistent words) were further manipulated: words with a high summed frequency of Friends and a low summed frequency of enemies (HFLE), and words with a low summed frequency of friends and a high summed frequency of enemies (LFHE) were equally distributed in inconsistent words. The results showed that neighborhood properties matter for the consistency effect in naming performance whereas the regularity influenced accuracy only and its influence was restricted to words with LFHE. Specifically, the consistency effect (the difference between inconsistent words, including both exception-inconsistent and regular-inconsistent, and matched regular consistent words) was larger when inconsistent words had LFHE than when inconsistent words had HFLE.

Moreover, when inconsistent words have LFHE, this consistency effect was also observed in high-frequency words (Experiment 2 and 3, see also Jared, 1997). By contrast, only when the inconsistent words had LFHE did regular-inconsistent words obtain higher accuracy than exception-inconsistent words. Therefore, Jared (2002) argued that consistency, as well as neighborhood properties, are dominant factors in affecting English word naming, whereas regularity has only a small contribution.

1.2 Consistency and regularity in Chinese reading

Aliquam Written Chinese, a logographic script, presents a sharp contrast to written English and other alphabetic languages. Chinese characters map onto monosyllables rather than phonemes and their sub-lexical units (i.e. radicals) can represent a syllable, a morpheme or both. Specifically, there are two types of Chinese characters: simple characters, which have only one orthographic component and compound characters, which have more than one orthographic component. As many as 80 percent Chinese characters are phonetic compounds (Zhou, 1978), i.e., phonograms (e.g., 植, ‘zhi2’ , plant), which consist of two functional components: the phonetic radical (直, ‘zhi2’, vertical), which provides cues to the pronunciation of the host character and the semantic radical (木, ‘mu2’ , wood related), which implies 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.

However, the orthography-to-phonology mappings of written Chinese can also be characterized by consistency and, at least on some interpretations, also regularity[1]. A consistent character (e.g., 浓) is homophonic with all of its orthographic neighbors (e.g., 浓, 侬, 脓, 哝), i.e., those sharing the same phonetic radical (e.g., 农); an inconsistent character (e.g., 距) has at least one non-homophonic orthographic neighbor (e.g., 柜) sharing the same phonetic radical (e.g., 巨, Fang, Horng, & Tzeng, 1986; Hue, 1992; Lee et al., 2004). The degree of consistency, the extent to which the pronunciation of a character (e.g., 距) is congruent with pronunciations of its orthographic neighbors (e.g., 距, 拒, 柜, 矩, 炬, 钜 all share the radical 巨), can be quantified by either the type consistency[2] or the token consistency[2](e.g., Hsu, Tsai, Lee, & Tzeng, 2009; Lee, Tsai, Su, Tzeng, & Hung, 2005). For example, the character 炬 ('ju3'), has 5 friends (i.e., 5 homophonic orthographic neighbors: 炬, 距, 拒, 矩, 钜, with their character frequencies of 12, 98, 74, 16, and 1 per million, respectively), and 1 enemy (i.e., 1 non-homophonic orthographic neighbor: 柜, 'gui4', with its character frequency of 44 per million). Thus, it has a type consistency value of 5/(5+1) = 0.83 and a token consistency value of (98+74+16+12+1)/(98+74+16+12+1+44) = 0.82. The "enemy" character 柜: 'gui4', has a type consistency value of 1/(5+1)=0.17 and a token consistency value of 44/(98+74+16+12+1+44) = 0.18. Phonograms with high type and token

[1] Some scholars (e.g., Perfetti, Zhang & Berent, 1992) used "phonemic validity" instead of regularity in describing the phonological relationship between host character and its phonetic radical: compound characters, which were pronounced the same as one of its components, were said to have "phonemic validity".

[2] The type consistency of a character refers to the ratio of the sum of friends (including the character itself) to the sum of both friends and enemies; the token consistency of a character refers to the ratio of the summed token frequencies of friends (including the character itself) to the summed token frequencies of both friends and enemies.

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 possible analogy with English, the regularity of a character has been defined in terms of the phonological relationship between the host character and its phonetic radicals (Zhou & Marslen-Wilson, 1999). Unlike English, however, regularity in Chinese is not applied to all characters, but only to the subset of phonograms, which contain a phonetic radical that can stand alone as a legal character. For instance, the phonogram 呱 ('gua1', a sound) is a regular character because it is pronounced identically with its phonetic radical 瓜 ('gua1', melon) in terms of both the syllable and tone. Again, in contrast to English, phonological relations have been generously categorized along approximations to pronunciation. Thus, the phonogram 村 ('cun1', village) is a semi-regular character because its pronunciation shares the same syllable with the pronunciation of its phonetic radical 寸 ('cun4', inch) but differs in tone; the phonogram 松 ('song1', loose) is a rhyming character because it rhymes with its phonetic radical 公 ('gong1', public); the phonogram 横 ('heng2', horizontal) is a alliteration character because its pronunciation shares the same consonant with the pronunciation of its phonetic radical 黄 ('huang2', yellow) but differs in vowels; the phonogram 钮 ('niu3', button) is an irregular character because it is pronounced entirely different from its phonetic radical 丑 ('chou3', ugly) in terms of both consonants and vowels (see definitions in Zhou & Marslen-Wilson, 1999).

Because phonograms consist of phonetic radicals that can stand alone as legal characters, they can be characterized by both consistency and regularity. Thus, Chinese allows a factorial design with consistency and regularity orthogonally manipulated, something not possible in

English, which lacks examples of irregular (exception)-consistent because of the dichotomous definition of consistency. For instance, the high consistency character 炬 is a regular high consistency character because it is homophonic with its phonetic radical 巨; the irregular character 钮 is an irregular high consistency character because it is homophonic with most of its orthographic neighbors, 妞, 扭, 忸, 纽; the regular character 呱 is a regular low consistency character, because it is pronounced differently from most of its orthographic neighbors, 孤, 弧, 狐, 抓; the low consistency character 柜 is an irregular low consistency character, because it is pronounced differently from its phonetic radical 巨 in terms of both consonant and vowels. However, this exhaustive combination of levels of consistency and regularity has not characterized research in English because it lacks exception words that are consistent.

1.3 Previous research on the consistency and regularity in Chinese reading

1.3.1 Behavioral studies

Early behavioral research in Chinese character naming examined solely the role of regularity (e.g., Seidenberg, 1985) and found that regularity interacted with frequency in character naming–Regular characters were named faster than simple characters (Seidenberg, 1985) and irregular characters (Experiment 2 in Hue, 1992) in naming low-frequency characters only, not in naming high-frequency characters.

Subsequent research in Chinese reading borrowed a lot from alphabetic reading research. Similar to the design in Jared (2002), the relative contribution of consistency and regularity has been examined by comparing the naming responses to three types of characters: regular-consistent, regular-inconsistent and irregular-inconsistent characters (Fang et al., 1986; Experiment 3 in Hue, 1992; Lee et al., 2005). Significant consistency effects without regularity effects were found in low-frequency characters but not in high-frequency characters (Fang, 1986; Hue, 1992): Regular-consistent characters were named significantly faster than regular-inconsistent characters, whereas the naming latency of regular-inconsistent characters did not differ from that of irregular-inconsistent characters (i.e., no regularity effect). However, neither Fang (1986) nor Hue (1992) controlled neighborhood properties. Following Jared (2002), Lee et al., (2005) further controlled neighborhood properties and found the same consistency effects in both high- and low-frequency characters. Meanwhile, a regularity effect was observed in low-frequency characters, but not in high-frequency characters. Echoing Jared (2002), Lee et al., (2005) argued that consistency performed better than regularity in representing the orthography-to-phonology mappings of Chinese characters because (1) the consistency effects in character naming were not constrained by word frequency, and (2) consistency could apply to all phonograms, whereas the regularity was restricted to phonograms containing phonetic radicals that could stand alone as legal characters (see also Lee, 2008).

1.3.2 Event related potential (ERPs) studies

ERP components have been associated with different stages of word recognition in prior research. For instance, the N170 has been suggested to reflect fast orthographic detection at the initial stage of perceptual categorization (e.g., Bentin et al., 1999; Wong, Gauthier, Woroch, Debuse, & Curran, 2005) and automatic connections between orthographic forms and phonological representations in word recognition (e.g., Maurer & McCandliss, 2007; McCandliss

& Noble, 2003). The P200 has been associated with early orthographic and phonological processing in visual word recognition (e.g., Barnea & Breznitz, 1998; Kong et al., 2010). The N400 is well-known for its association with semantic processing (Lau, Phillips, & Poeppel, 2008) and also has been associated with the integrative process among various sources of information, including phonological information (e.g., Barnea & Breznitz, 1998; Rugg & Barrett, 1987). Thus, ERPs can provide evidence of consistency and regularity at different time points during word recognition, indexed by their impacts on N170, P200 and N400 responses.

However, results of ERP research on Chinese reading diverged on the relative contributions of consistency and regularity. Some studies (e.g., Hsu et al., 2009; Lee et al., 2007), found that consistency modulated various ERP responses to characters during covert naming. For instance, in a homophone judgment task, participants judged whether the target was homophonic with the following probe character; low consistency characters were found to elicit greater N170, greater P200 and smaller N400 than high consistency characters (Lee et al., 2007). In addition, when phonetic combinability was further manipulated orthogonally with consistency, the P200 and N400 responses were affected by consistency only, whereas the N170 response was modulated by both phonetic combinability and consistency: Only when the characters were high consistency did high phonetic combinability characters elicit a greater N170 than low phonetic combinability characters.

However, a more recent ERP study (Yum, Law, Su, Lau, & Mo, 2014) emphasized the role of regularity over consistency, by showing early and lingering regularity effects on N170, P200 and N400 in contrast to a relatively transient consistency effect observed on only the P200 only. Yum et al., (2014) stressed the role of regularity because it showed effects comparable the consistency effects reported in Hsu et al., (2009) and argued that the consistency effects in Lee et al., (2007) and Hsu et al., (2009) were likely confounded with regularity. Indeed, none of these ERP studies on consistency effects have reported the regularity of characters.

However, we have several reasons to be cautious about these conclusions. Specifically, Yum et al., (2014) manipulated either consistency or regularity while controlling the other factor in two sets of characters. First of all, word frequency differences between the two sets of characters may affect their observations of consistency and regularity effects. In other words, the obtained persistent regularity effect in contrast with the transient consistency effect may be because the stimuli in examining regularity effect have more low-frequency characters than those in examining consistency effect; after all, both consistency and regularity effects are stronger in low-frequency characters than in high-frequency characters. However, each set of stimuli in their study includes both high and low frequency characters, and comparisons on word frequency between the two sets of stimuli have not been reported. Moreover, the stimuli (N = 55) in examining regularity effect outnumber those (N = 36) in examining consistency effect; with a larger number of stimuli in examining regularity effect than consistency effect and uncontrolled word frequency, it is no wonder that the observed regularity effect is robust and persistent, whereas the consistency effect only appears on P200 only. Furthermore, according to the reported accuracy of delayed naming, it seems that not all characters are named correctly by all participants. So, participants may not even know some characters or may have incorrect pronunciations for some characters; ERP data without excluding these characters may be misleading. Therefore, a comprehensive study, directly examining the relative contribution of consistency and regularity in a single experiment with all the above-mentioned concerns considered, is desirable.

1.4 The current study

The current study used ERPs to directly examine this issue in Chinese reading in a single set of characters in a complete orthogonal design that included irregular high consistency characters to allow a more complete picture of effects in Chinese reading. The task required phonology but did not require naming. Participants saw two sequentially presented characters and were asked to name covertly the first character and when the second character appeared, judge whether its pronunciation was the same as the first character. ERP data was time-locked to the first character, of which the consistency and regularity were orthogonally manipulated. All target characters were of low frequency so that both consistency and regularity effects could be observed. After the ERP experiment, participants' knowledge of pronunciations of the characters was tested.

We tested two hypotheses regarding the relative roles of consistency of regularity in Chinese reading. One hypothesis, in line with studies of Hsu et al., (2009) and Lee et al., (2007), is that consistency is the dominant factor in affecting stages of orthographic, phonological and semantic processing during character naming, and its importance would be shown in the N170, P200 and N400 responses. An alternative hypothesis, in agreement with the study of Yum et al., (2014), is that regularity is the dominant factor. If this hypothesis is true, regularity of characters would affect the accuracy of posttest and modulate the N170, P200 and N400 responses. In addition, it is possible that consistency and regularity contribute jointly to word recognition in character naming, but previous research with non-orthogonal designs is not able to capture this possibility. If this is the case, an interaction between consistency and regularity would be expected in modulating ERP responses during word recognition as well as in affecting the accuracy data of posttest.

2.0 Materials and methods

2.1 Participants

Thirty-six undergraduate students (16 males; mean age 19, range 18–22) from the University of Pittsburgh with normal or corrected-to-normal vision took part in the ERP experiments. All participants grew up in Mainland China, and are right-handed, native Mandarin speakers. ERP data of five participants (3F) were excluded due to excessive artifact rejection (at least one condition with less than 17 trials after artifact rejection). On average, each condition had 30 trials after posttest accuracy correction and artifact rejection.

2.2 Materials

The critical stimuli consisted of 184 low-frequency (below 40 per million) target characters, which were equally distributed in four groups (46 characters in each group, see Table 1) that resulted from the orthogonal manipulation of consistency (high vs. low) and regularity (regular vs. irregular). For consistency, token consistency was the primary selection criterion and type consistency was the secondary selection criterion. In particular, the token consistency value of 0.44 was the cutoff value for high- and low- consistency characters. Moreover, all low consistency characters had a type consistency value less than 0.5. For regularity, all regular characters shared the same syllable with their phonetic radicals (ignoring any tonal differences), whereas irregular characters did not. In addition, these four groups of characters were matched in terms of visual complexity (i.e., the number of strokes), phonetic combinability , homophone density , semantic concreteness and radical token frequency (see Table 1).

Table 1. Sample stimuli

Target conditions				
Consistency	**High consistency**		**Low consistency**	
Regularity	**Regular**	**Irregular**	**Regular**	**Irregular**
Sample character	咏 ***/yong3/ chant***	钮 ***/niu3/ button***	怅 ***/chang4/ disappointed***	贿 ***/hui4/ bribe***
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)
Phonetic radicals token frequency (per million) Range: [min, max]	永 673.5 (958.4) [0.9, 4702.9]	丑 674.1(1128.3) [3.1, 6315.5]	长 661.2 (1427.7) [2.1, 8895.8]	有 619.6 (1283.4) [2.6, 8159.0]

2.3 Procedure

Each trial started with a fixation cross displayed for 300ms, followed by the target character for 800ms. After a 800ms blank, the probe character appeared and remained on the screen until manual responses. The inter-trial interval was 1800–2200ms. Both characters were displayed in font Song, 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 room. Participants were instructed to name silently the target character in their mind, when the target character appeared. When the probe character appeared, participants were instructed to judge whether the target and probe characters were homophones or not by pressing a key.

The critical targets in each condition (46 characters) were randomly assigned into two separate lists so that half stimuli (23) in each condition were followed by homophonic probes and the other half (23) by control probes. Each target appeared once for each participant and the probe types were counterbalanced across participants. In total, participants completed 196 trials (184 critical trials and 12 fillers) in 6 blocks. Each block started with 2 filler trials, followed by randomized critical trials (equally distributed in homophone and control conditions). The first five blocks consisted of 32 critical trials and the final block 24 critical trials. For each block, the critical trials were equally distributed in homophone and control conditions for each of the four types of targets (4 trials for each condition in the first 5 blocks and 3 trials for each condition in the final block).

2.4 EEG recording and preprocessing

EEG recordings were made from a 128 electrode Geodesic sensor net with Ag/AgCI electrodes (Electrical Geodesics, Inc., Eugene, OR) at the sampling rate of 1000 Hz. During recording, all impedances were kept below 40 kΩ. A vertex reference was used during the recording.

2.5 Data analyses

For the online (i.e., ERP experiment) and offline (i.e., the posttest questionnaire) accuracy data, mixed effect logistic regression modeling was applied using maximum likelihood (ML) estimation: The online accuracy referred to whether or not the participant made correct judgement on the homophone and control trials and the offline accuracy whether or not the participant correctly transcribed the target character. For scoring the posttest, target characters were divided into known (i.e., correct items) and unknown (wrong or unknown items) items. For the online accuracy, mixed effect logistic regression modeling was performed separately for known and unknown items. The online RTs data included only known items in analyses and RTs beyond 2 standard deviations from the sample mean were excluded from analyses. After this, mixed effect linear regression was applied to online RTs data, recorded from the appearance of the probe characters. For all mixed effect modelings, the final model was obtained by using the likelihood-ratio test in comparing a model with fixed effects of regularity (regular vs. irregular) and consistency (high vs. low) and their interaction, with nested simple models (see details in appendix). The contrasts of dummy variables were set as 0.5 and -0.5 so that one unit change reflected the main effect of each factor. Random effects of both subjects and items were included.

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. In addition, unknown items of the posttest questionnaires were excluded from EEG data for each participant. ERPs were computed for correct trials after ocular artifact rejection. Each epoch lasted 1100ms, including a 100ms baseline interval prior to target onset. Mean amplitude across 100–150ms, 170–260ms, 300–450ms, 500-800ms time windows, were calculated for N170, P200, N400 and LPC, respectively. The N170 amplitude at parietal (P3/z/4 clusters) and occipital (O1/z/2 clusters) regions, the P200 amplitude at frontal (F3/z/4 clusters), central (C3/z/4 clusters), and parietal regions, the frontal N400 (FN400) amplitude at frontal region, the central-parietal N400 amplitude at central and paritetal regions, and LPC at frontal, central and parietal regions were analyzed with a four-way ANOVA with target regularity (regular vs. irregular), consistency (high vs. low), laterality (left, midline, right), and region as within-subject factors. Greenhouse-Geisser correction was applied to all repeated-measures with more than one degree of freedom. Any three-way interactions containing the factors of consistency and regularity were followed by separate analyses at the high consistency and low consistency levels to further examine the consistency effect, and by separate analyses at regular and irregular levels to further examine the regularity effect. Any two-way interactions were followed by simple main effect analyses and overall pair-wise comparisons across all electrodes with Bonferroni adjustment.

3.0 Results

3.1 Posttest accuracy

3.1.1 Offline accuracy

On average, high consistency targets obtained higher (+8%) accuracy than low consistency targets (see figure 1), and the final mixed logit model (see details in table 2) showed that consistency had a significant effect on the logits of correctly transcribing target characters after the variances associated with subjects and items were simultaneously controlled. In addition, regular targets obtained higher (+3%) accuracy than irregular targets (see figure 1); however, the effect of regularity ($p > .1$) was non-significant in the final mixed logit model.

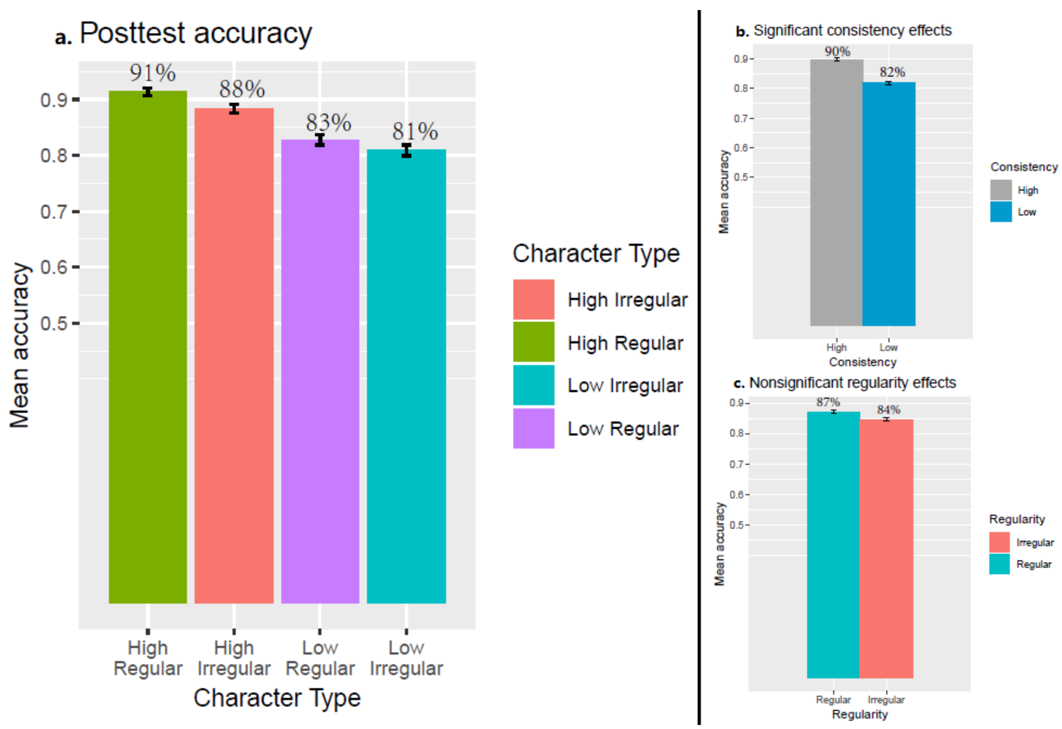

Figure 1 Results of offline accuracy (i.e., accuracies in the posttest questionnaire)

Table 2. Details of the final mixed effect models: a. offline accuracy of all items in posttest, b. online accuracy for known items, c. online RTs for known items, and d. online accuracy for unknown items

a. Offline accuracy in posttest

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. Online accuracy for known items (correct items in posttest)

Logit of correct judgement ~ 1 + Regularity + Consistency +Probe condition + (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 condition	2.02	0.17	11.74	**< . 001**

c. Online RTs for known items (correct items in posttest)

RTs ~ 1 + Regularity + Consistency + Probe condition + (1|Subject) + (1|Item)

Predictor	Coefficient	SE	Wald Z	*p* value
Intercept	819.97	32.32	25.37	**< . 001**
Regularity	2.515	11.22	0.22	.82
Consistency	5.38	11.22	0.48	.63
Probe condition	30.23	6.96	4.34	**< .001**

d. Online accuracy for unknown items

Logit of correct button press ~ 1 + Regularity + Consistency +Probe condition + (1|Subject) + (1|Item)

Predictor	Coefficient	SE	Wald Z	*p* value
Intercept	2.19	0.24	9.13	**< . 001**
Regularity	-0.87	0.31	-2.80	**< . 05**
Consistency	1.07	0.32	3.38	**< . 001**
Probe condition	5.27	0.40	13.02	**< . 001**

3.1.2 Online accuracy and reaction times (RTs)

Known items

The known items were characters that participants transcribed correctly during the posttest questionnaire. On average, the accuracy of control trials that required a '*no*' response approached ceiling (*mean* = 98%, *SD = 12%*) for all types of targets (see figure 2); the accuracy of homophone trials was relatively lower (*mean* = 90%, *SD = 29%*) with more variance. For RTs, on average, homophone trials were reacted faster (-30.23 ms) than control trials (see figure 2). These probe type effects (*ps* <.05) were confirmed in the mixed effect logistic regression model on online accuracy and the mixed effect linear regression model on RTs (see details in table 2). However, the effects of neither consistency ($p > .1$) nor regularity ($p > .1$) were significant in the final models on online accuracy and RTs after the variances associated with subjects and items were simultaneously controlled for.

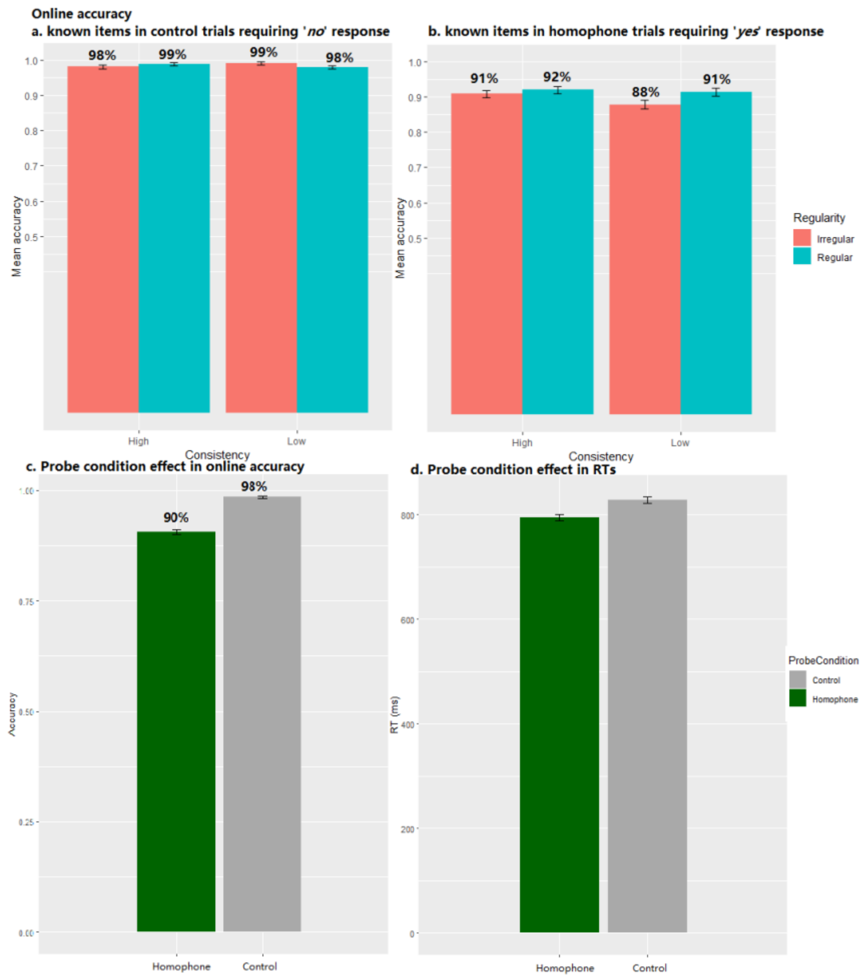

Figure 2 Online accuracy and RTs for the known items

Unknown items

The unknown items were characters that participants marked as unknown or transcribed incorrectly during the posttest questionnaire. On average, participants obtained high accuracy in rejecting the control trials (see figure 3), even if they didn't know the items. By contrast, the accuracy of judging a homophone trial was low, when they didn't know the items. In particular, homophone trials involving regular high consistency characters (56%) were judged more accurately than those involving both regular low consistency (40%) and irregular high consistency

(40%) characters, and homophone trials containing unknown irregular low consistency characters obtained least accuracy (18%).

The final mixed logit model for online accuracy of unknown items (see details in table 2) show that the effects of consistency (p <.001), regularity (p <.05), and probe condition (p <.001) were all significant after the variances associated with subject and items were simultaneously controlled. Specifically, trials involving high consistency characters significantly increased the odds $\frac{p(correct)}{(1-p(correct))}$ by 2.91 $(\text{i.e.}, e^{1.07})$ times in comparison with trials involving low consistency characters; trials involving regular characters significantly increased the odds $\frac{p(correct)}{(1-p(correct))}$ by 2.39 $(\text{i.e.}, e^{0.87})$ times in comparison with trials involving irregular characters.

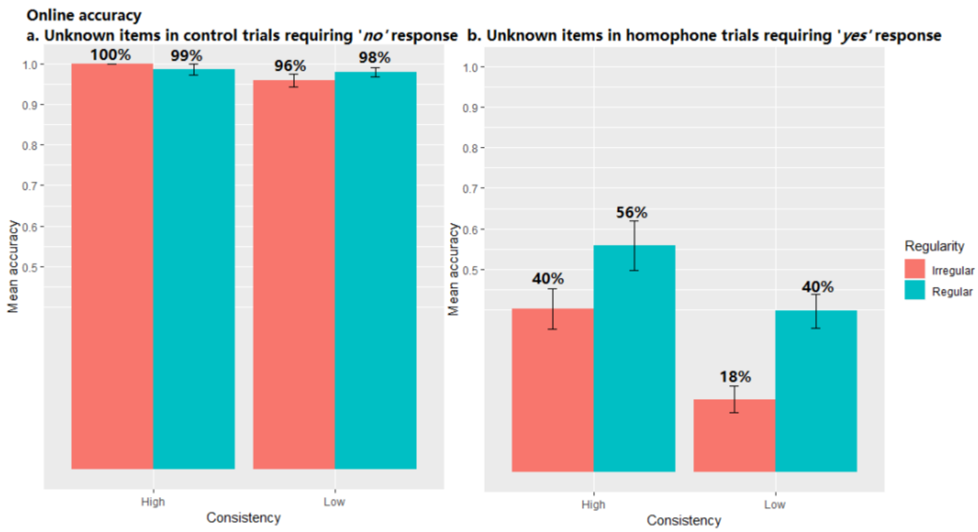

Figure 3 Online accuracies for unknown items

3.2 ERP results

3.2.1 N170

The results showed significant consistency effect on the N170 (for details of ANOVA, see table 3): High consistency characters elicited less negative going (+0.297 μV) N170 than low consistency characters (see figure 4). 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 ($p > .1$), midline area ($p > .1$) or right hemisphere ($p > .1$).

Table 3. Results of the four-way repeated measure ANOVA for all ERP components (only main effects and interactions involving either consistency or regularity are shown)

	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 = .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 = .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 = .93, p < .05 (consistency effect: midline, *p* < .001, left hemisphere, *p* < .001, right hemisphere, *p* > .1)
FN400	consistency × regularity: F(1, 30) = 4.96, MSE = .88, p < .05 **consistency× regularity × laterality**: F(1.82, 54.60) = 5.34, MSE = .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

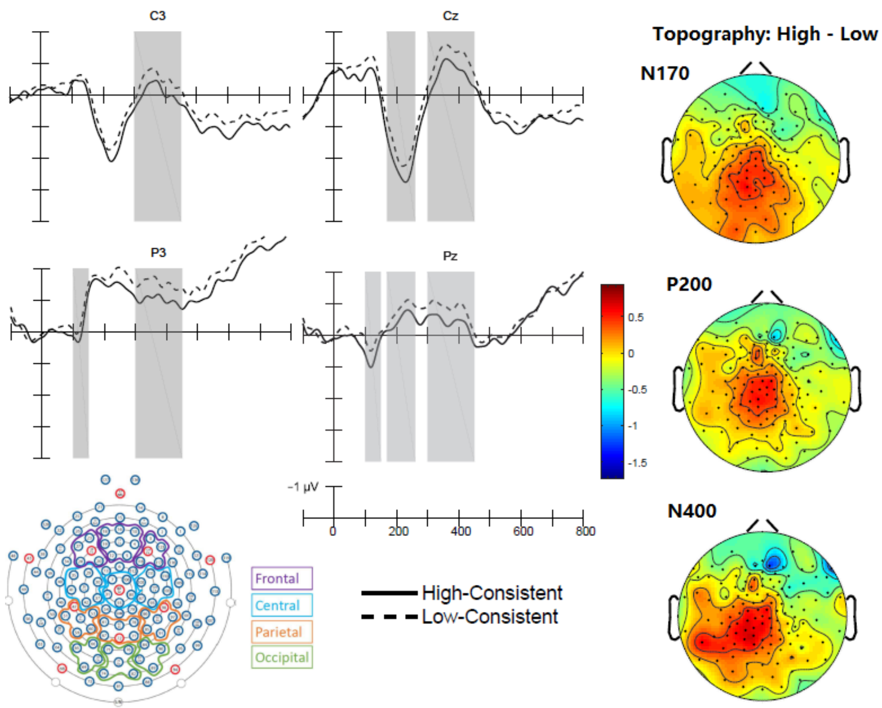

Figure 4 Consistency effects on the N170, P200 and N400 components

3.2.2 P200

The results showed a significant consistency effect on the P200 (for details of ANOVA, see table 3): High consistency characters elicited more positive going P200 than low consistency characters (see Figure 4) and this effect was significant in the midline area ($p < .025$), marginally significant in the left hemisphere ($p < .05$), but not significant in the right hemisphere ($p > .1$). However, no effect of regularity was observed (*ps* > *.1*).

3.2.3 Central-parietal N400

The results showed a significant consistency effect on the N400 (see table 3): High consistency characters elicited a less negative going N400 than low consistency characters (see Figure 4) in the midline (+ 0.46 μV, $p < .001$) and the left hemisphere (+ 0.49 μV, $p < .001$), but not in the right hemisphere ($p > .1$). However, no effect of regularity was observed.

3.2.4 Frontal N400 (FN400)

The results showed that consistency interacted with regularity (Consistency × Regularity × Laterality: $F(1.82, 54.60) = 5.34$, $MSE = .36$, $p < .05$) in modulating the FN400 (for details of ANOVA, see table 3): High consistency characters elicited more negative going FN400 than low consistency characters (see figure 5), and this consistency effect (–0.58 μV) was significant (Fz: $p < .05$ and F4: $p < .001$) for regular characters only, but not for irregular characters; similarly, regular characters produced more negative going FN400 than irregular characters, and this regularity effect (–0.69 μV) was significant (Fz: $p < .05$ and F4: $p < .001$) for high consistency characters only, but not for low consistency characters.

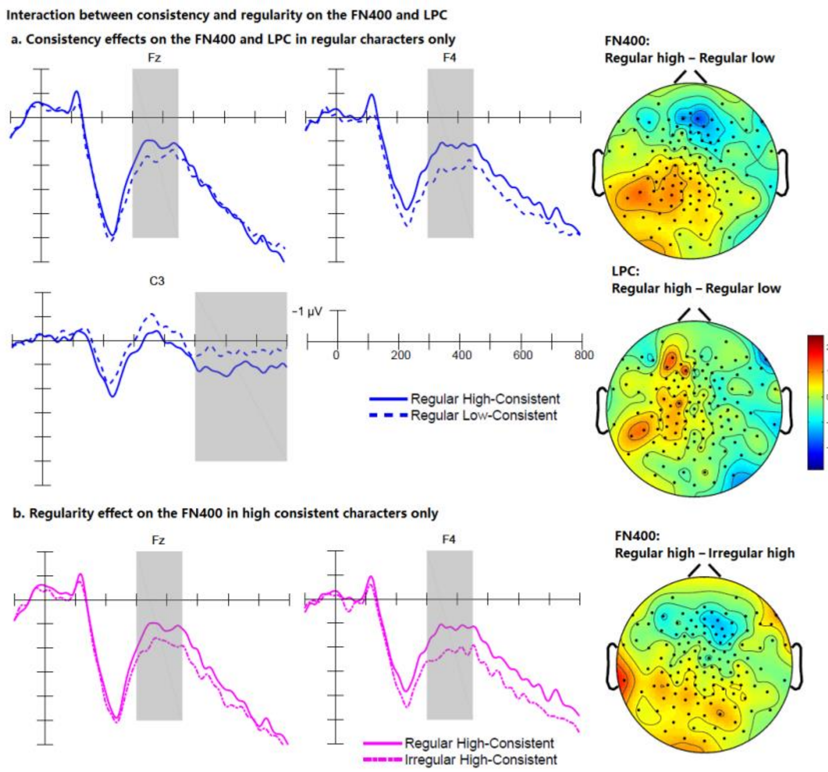

Figure 5 Impacts of consistency and regularity on the FN400 and LPC components

3.2.5 Late positive complex (LPC)

The results showed that consistency interacted with regularity (Consistency × Regularity × Laterality: $F(1.72, 51.54) = 4.74$, $MSE = 1.20$, $p < .05$) in modulating the LPC (for details of ANOVA, see table 3): High consistency characters elicited more positive LPC than low consistency characters (see figure 5), and this consistency effect (+0.535 μV) was significant (left hemisphere: $p < 0.05$) for regular characters only, but not for irregular characters. However, the effect of regularity was non-significant.

To summarize, consistency affected the N170, P200 and N400 responses during word recognition as well as the posttest accuracy in transcribing character pronunciations. Compared with low consistency characters, high consistency characters were transcribed more accurately in the posttest questionnaire and elicited less negative going N170 in parietal-occipital region, more positive-going P200 in the midline area, and less negative-going N400 in the left and midline, central-parietal area. In addition, consistency interacted with regularity in modulating the FN400 and LPC responses. Specifically, high consistency character induced more negative going FN400 and more positive going LPC in the left hemisphere than low consistency characters and this consistency effect was observed in regular characters, but not in irregular characters. However, regularity mattered for the FN400 only, but not the LPC: regular characters elicited more negative going FN400 than irregular characters, and this regularity effect was observed in high consistency characters, but not in low consistency characters.

4.0 Discussion

The present ERP study examined the relative contributions of consistency and regularity in Chinese character naming by manipulating the two factors orthogonally in a single set of stimuli. Our results showed that consistency, but not regularity, affected the electrophysiological responses during covert naming as well as behavioral performance in transcribing characters' pronunciations. Behaviorally, participants achieved significantly higher accuracy for high consistency characters than low consistency characters in posttest questionnaires. Electrophysiologically, high consistency characters elicited less negative going N170 in the parietal region, more positive going P200 in the midline area, and less negative going N400 in both left hemisphere and midline areas, in comparison with low consistency characters. These results suggest that consistency play a more important role than regularity in character recognition.

However, it seemed that the role of regularity was not entirely muted in character recognition. The FN400 and LPC in covert naming was modulated by both consistency and regularity: high consistency characters induced more negative going FN400 in the Fz and F4, and more positive going LPC in the left hemisphere than low consistency characters; however, this consistency effect was observed in regular characters only, not in irregular characters. Similarly, regular characters elicited more negative going FN400 than irregular characters in the Fz and F4; however, this regularity effect was observed in high consistency characters only, not in low consistency characters. No regularity effect was found for the LPC.

In the following, we first discuss how the consistency and regularity of Chinese characters play a role in a model of character recognition proposed by Taft and colleagues (Ding, Peng, & Taft, 2004; Taft, 2006; Taft, Zhu, & Ding, 2000), which is helpful in framing the discussion of the behavioral and ERP effects. We then discuss the question of why consistency has a much greater influence on Chinese character naming than regularity.

4.1 The role of consistency and regularity in a character recognition model

The relationship between the orthographic representation of a complex character and that of its phonetic radicals, which has been addressed in Taft's model, is critical in illustrating the role of consistency and regularity. In particular, this model assumes that there are three subsystems (orthography, phonology and semantics), which are mediated by a layer of lemma units (see figure 6).

Of particular interest in illustrating the role of consistency and regularity is the hierarchical orthographic subsystem, which involves representations of complex characters and those of their radicals. Specifically, complex characters have representations at the lexical level and their radicals at the sub-lexical level. When the radical can stand alone as legal characters, it has one lexical representation and one radical representation, which are connected with each other (see figure 6). For example, the complex character 钮 (in blue) consists of a phonetic radical 丑, which also can stand alone as a legal character. 丑 has a lexical representation (in orange) at the lexical level, which connects to its lexical meaning and pronunciation via a lemma unit, and a radical representation (in black) at the sub-lexical level, which connects to the complex character 钮 that contains it as a radical (for justifications see Taft et al., 2000).

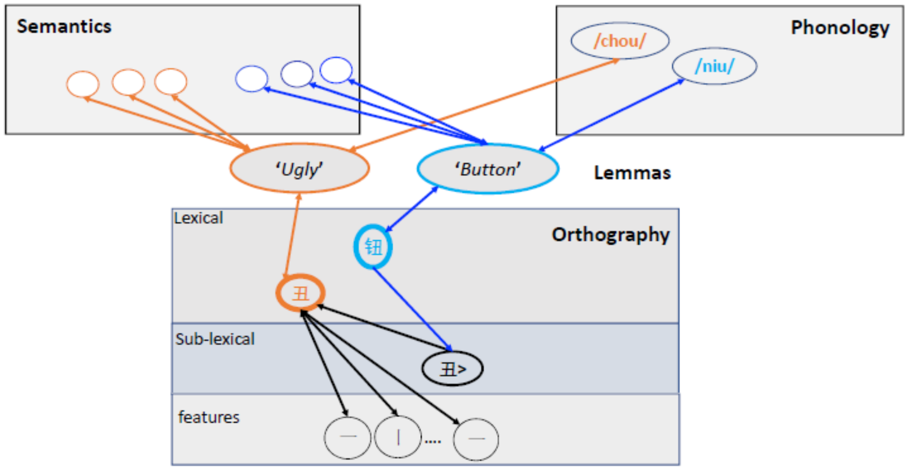

Figure 6 Illustration of the complex character '钮' with Taft's model (see explanations in text)

Consider the consistency and regularity in Taft's model (see figure 7): A high consistency character (e.g., 炬) has its orthographic representation (in blue and bold) connecting to the same phonological representation (in blue) as most of its orthographic neighbors (e.g., 距, 拒, 钜, 矩), which are homophonic with 炬 (see figure 7). In contrast, a low consistency character (e.g., 呱) has its orthographic representation (in green and bold) connecting to a phonological representation (in green) that is different from the phonological representations (in red) of most of its orthographic neighbors (e.g., 弧, 孤, 狐, 抓), which are not homophonic with 呱. A regular character (e.g., 柜) has a phonological representation that also connects to the lexical orthographic representation (in purple) of its phonetic radical (e.g., 巨). By contrast, an irregular character (e.g., 钮) has its phonetic radical's lexical orthographic representation (in orange, e.g., 丑) connect to a different phonological representation (in orange).

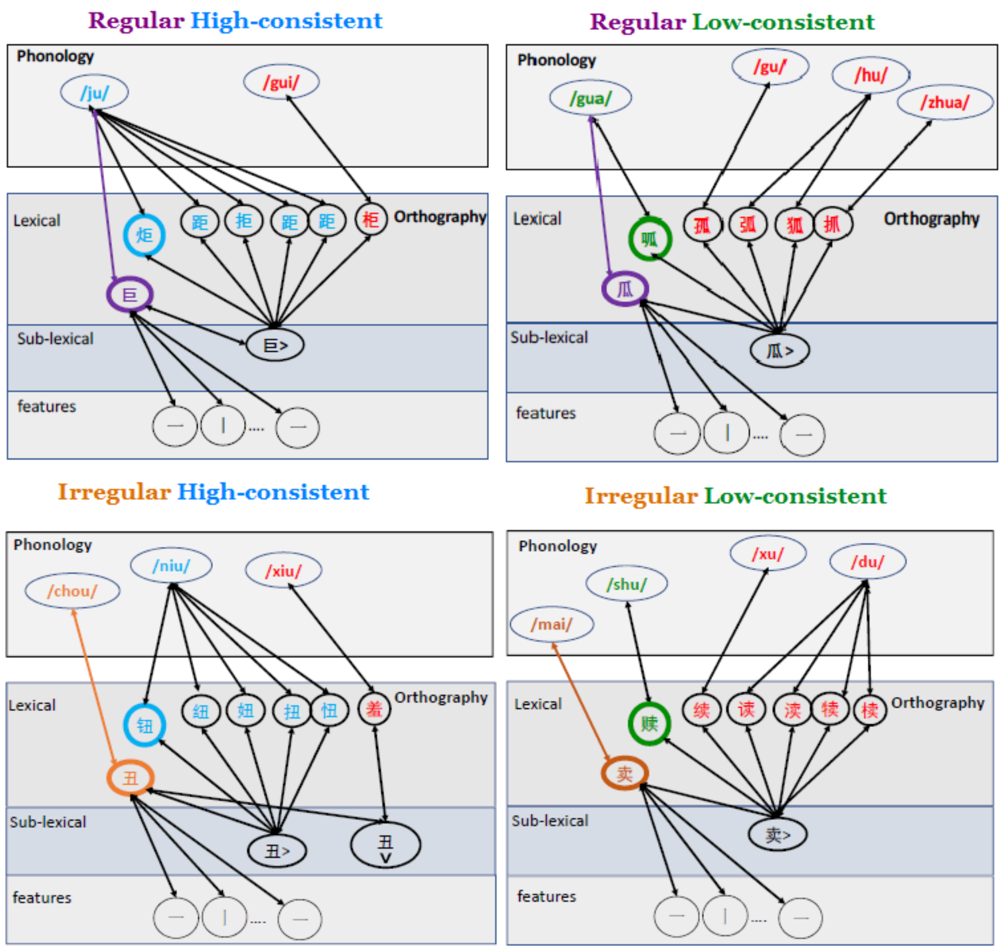

Figure 7 Illustrations of consistency and regularity effects in Taft's model. Note: The lemma subsystem and semantic subsystem are omitted to illustrate the orthography-to-phonology mappings. The left panels illustrate high consistency characters (in bold, blue), which have several orthographic neighbors connecting to the same phonological representations; the right panels illustrate low consistency characters (in bold, green), which have several orthographic neighbors connecting to different phonological representations; the top panels illustrate regular characters, whose phonetic radicals (in purple) connect to the same phonological representations; the bottom panels illustrate irregular characters, whose phonetic radicals (in orange) connect to different phonological representations.

In this framework, the roles of both consistency and regularity become clear by considering character-based and radical-based bottom-up and top-down processes (see figure 7). Specifically, character recognition can proceed in both direct character-based identification and radical-based identification. For radical-based identification, a bottom up process involves first activating the radicals, which activate the host character, and thus the host character's phonological representation. Once the host character's phonological representation is activated, a top-down process involves sending feedback from the character's phonological representation to all connected character-level orthographic representations, thus facilitating the orthographic activation of all its friends. Similarly, for character-based identification, direct recognition of the host character would activate its phonological representation in bottom-up manner and also send excitatory information to its radicals' sublexical level, orthographic representations in top-down manner.

Consider the role of consistency during the radical-based, bottom-up process: The phonological representation of a high consistency character would be accessed more rapidly than a low consistency character, because it gains activation from a larger number of friends (see figure 7), producing the consistency effect. Meanwhile, the phonological activation of high consistency characters can be accelerated by their friends of high frequency, whose orthographic activation could be rapid enough to activate the shared phonological representation. By contrast, low consistency characters are less likely to have such high frequency friends, because the token consistency value suggests that the friends have a low summed frequency of friends. Regarding the role of regularity in the radical-based, bottom up process: Identification of the phonetic radical, which can in turn activates its phonological representation, would benefit the phonological activation of regular characters, but inhibit that of irregular characters, producing the regularity effect.

Similarly, during top-down processes, where the activated phonological representation sends feedback information to all connected orthographic representations (see Figure 7), consistency and regularity may also play a role. Specifically, the top down process from the character's phonological representation could facilitate orthographic processing of all friends, but not all its friends will be activated to the same degree. Consider a high consistency character. When it is of low frequency itself, its friends of high frequency are likely to have their orthographic representations activated during this top-down process, which in turn induces interference with the character's orthographic processing. Low consistency characters are less likely than high consistency characters to have such high frequency friends due to a limited number of friends and low summed frequency of friends. Regularity may play a similar role in this process. The top down process from a character's phonological representation can directly send excitatory to the lexical representation of its phonetic radical when it is a regular character, but not when it is an irregular character. During this process, regular characters' phonetic radicals may have the radicals' lexical orthographic representation activated rapidly and produce interference to the orthographic processing of the host character.

The interaction of word frequency with both consistency and regularity can be explained by the extent to which word recognition proceeds in radical-based bottom-up manner. After all, the phonological representation of a character can be activated by both direct character-based identification and radical-based identification. Character frequency becomes relevant in affecting the balance between character-based and radical-based identification, with more direct character-based identification occurring for higher frequency characters. By contrast, reading low frequency characters would engage more radical-based identification, where the consistency and regularity play a role. In addition, for low frequency characters, the character-based identification may not be rapid enough to stabilize the connection between the orthographic and phonological representations, which make the character's orthographic processing vulnerable to any orthographic activation of its friends or radicals during top-down processes. These accounts for the findings that consistency and regularity effects are more prominent in low frequency characters than high frequency characters (e.g., Hue, 1992), parallel to findings for English words (e.g., Seidernberg, 1985).

4.2 Behavioral effects of consistency and regularity in character recognition

Behaviorally, our posttest showed that the knowledge of character pronunciations was affected by consistency only, but not regularity. High consistency characters obtained higher accuracy than low consistency characters. We refer to those characters that are transcribed correctly by participants as known items and to the others as unknown items. These results were in agreement with prior research with overt naming task, which shows that consistent characters were named faster than inconsistent characters (e.g., Lee et al., 2005).

One noticeable result was that probe type mattered for both known and unknown items. For known items, homophone trials were reacted to faster (-30 ms) but less accurately (-8%) than control trials. This significant probe type effect may simply reflect a compromise between accuracy and RTs. By contrast, for unknown items, the effect of probe type was much larger: Homophone trials (39%) were reacted to much less accurately (-59%) than control trials (98%). This large probe type effect may reflect a response bias: When participants had unsure phonological knowledge of a character (unknown items), they tended to say that the pair of items did not have the same pronunciation, which lead to correct responding on control trials and errors on homophone trials.

Interestingly, for unknown items, both consistency and regularity affected the judgment accuracy of homophone trials, although the accuracy for homophone trials was very low. Homophone trials involving high consistency characters obtained relatively higher accuracy (48%) than those involving low consistency characters (29%); similarly, homophone trials involving regular characters obtained relatively higher accuracy (48%) than those involving irregular characters (29%). These results suggested that, in the homophone judgment task, participants indeed extracted some phonological information during the radical-based bottom up process, of which both consistency and regularity played a role.

However, neither consistency nor regularity affected the online accuracy and RTs of known items. These differences between unknown and known items were probably because reading unknown items relied more heavily on radical-based bottom-up process due to the failure of direct character identification process. It is also possible that behavioral measures were just not sensitive enough to capture the effects of consistency and regularity during reading known characters, where parallel radical-based and character-based identification produce more complex interactive bottom-up and top-down processes. After all, our ERP measures on these known items indeed found effects of consistency and regularity.

4.3 ERP effects of consistency and regularity in character recognition

4.3.1 N170

Our main finding regarding the N170 is that high consistency characters elicit a less negative going N170 than low consistency characters in posterior area, which is consistent with the observation of Lee et al., (2007). However, different from Yum et al., (2014), no regularity effect on N170 is observed in our study.

In past research, the reading-related N170 has been reported to be sensitive to orthographic processing (e.g., Maurer, Brandeis, & McCandliss, 2005) as well as word properties such as word frequency (e.g., Hauk & Pulvermüller, 2004), consistency (e.g., Lee et al., 2007), regularity (e.g., Yum et al., 2014) and phonetic combinability (e.g., Hsu et al., 2009). However, the patterns of N170 effect were diverse, depending on the contrasts, and the underlying reasons are still unknown at present. For instance, regarding orthographic processing, an enhanced (i.e., more negative going) N170 effect has been consistently reported in contrasting words with other low-level visual control stimuli such as strings of meaningless symbols, forms and dots (e.g., Maurer et al., 2005), even in tasks that do not require explicit reading (e.g., Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). However, high frequency words were found to elicit reduced (i.e., less negative going) N170 compared with low frequency words (Hauk and Pulvermuller, 2004), although this reduced N170 effect might be related to general linguistic processing, not just orthographic processing (Maurer & McCandliss, 2007).

In general, there are two accounts, which are not mutually exclusive, regarding the N170 effect in word recognition. The perceptual expertise account of word related N170 (e.g., Lin et al., 2011; Tanaka & Curran, 2001; Wong et al., 2005) suggests that extensive reading experience lead to fast, automatic orthographic detection of words, as indexed by the N170 enhancement. For example, Wong et al., (2005) reported English monolingual readers showed an enhanced N170 effect in viewing Roman letters relative to Chinese characters and pseudofonts, whereas Chinese-English bilingual readers showed enhanced N170 effects for both Roman letters and Chinese characters relative to pseudofonts. This account was in accordance with the N170 effects in expert perception of other classes of visual stimuli such as faces and objects (e.g., Gauthier, Curran, Curby, & Collins, 2003). In addition, Lin et al., (2011) found that pseudo Chinese characters, wherein the radicals were (1) unpronounceable and (2) at their frequently appearing position, elicited an enhanced N170 effect (relative to random stroke combinations) that was comparable to that elicited by real characters. Hence a strong perceptual expertise account argued that the enhanced N170 effect could be driven solely by automatic orthographic analysis in word recognition, without the involvement of phonological processing.

The phonological mapping account (Maurer & McCandliss, 2007) of the N170 effect argued that it reflected automatic connections between orthographic forms and phonological representations in word recognition, a nonperceptual account of the N170 effect. This account can account for its sensitivity to word frequency (e.g., Hauk & Pulvermuller, 2004) and consistency (e.g., Lee et al., 2007) and regularity (e.g., Yum et al., 2014).

Our results of the reduced N170 effect for high consistency characters relative to low consistency characters may reflect faster automatic phonological processing of high consistency characters than that of low consistency characters, because high consistency characters have their phonological representations more accessible than low consistency characters via a larger number of friends during the radical-based bottom-up process(see figure 7). Therefore, our account is in agreement with the phonological mapping account, suggesting that the reading related N170 effect is not purely perceptual.

We noticed that the timing of N170 effect in our study, which started as earlier as 100 ms, was earlier than that reported in alphabetic languages (e.g., the word frequency N170 effect started from 150 ms in Hauk and Pulvermuller, 2004). This early timing of N170 effect was also reported in other ERP studies on character reading (e.g., Yum et al., 2014; Zhou et al., 2014). In addition, Liu and Perfetti (2003) found that the differences of ERP waveforms between Chinese character 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, which was referred to as N150. In our view, the N170 in our study may be similar to the reported N150 and the very earlier timing of the N170 in Chinese reading may be related to the script differences between Chinese and English as well as the proficiency level of participants.

4.3.2 P200

Our main finding regarding the P200 is that high consistency characters elicit more positive going P200 than low consistency characters. In past research, the P200 has been suggested to be associated with early orthographic and phonological processing (e.g., Barnea & Breznitz, 1998; Kong, Zhang, Zhang, & Kang, 2012; Kong et al., 2010). For instance, in a rhyming judgment task, Barnea and Breznitz (1998) found that rhyming Hebrew words pairs (including orthographic similar and dissimilar word pairs) induced enhanced P200 effect in comparison with orthographic dissimilar non-rhyming word pairs and they suggested this P200 effect indicated the extraction of orthographic and phonological features of words at the early stage of word recognition.

In the research with Chinese characters, orthographic and phonological similarities between character pairs seemed to induce different patterns on P200 (e.g., Chen et al., 2007; Liu et al., 2003; Kong et al., 2010; Kong et al., 2012): Orthographic similarity produced less positive-going P200 effect whereas phonological similarity induced more positive-going P200 effect. For instance, in a semantic judgment task, visually similar but non-homophonic, Chinese character pairs (e.g., 读 and 续) induced smaller P200 amplitude than control character pairs (e.g., 料 and 神), and this reduced P200 effect was also observed when the orthographic similar character pairs were simple characters (e.g., 目 and 且) without any shared radicals (Kong et al., 2012, see also Liu et al., 2003). By contrast, homophonic (at lexical level) but visually dissimilar Chinese character pairs (e.g., 雇 and 梏) elicit enhanced P200 effect relative to control character pairs (e.g., 甥 and 雇, Kong et al., 2010, see also Chen et al., 2007). In these studies, the reduced P200 effect was interpreted as reflecting facilitated orthographic processing and the enhanced P200 effect as reflecting facilitated phonological processing. These accounts were further supported by Zhou et al., (2014), where a reduced P200 effect was observed for irregular targets (e.g., 榛) when preceded by a character (e.g., 琴) homophonic with the radical (e.g., 秦) embedded in the target than when preceded by a control character (e.g., 罢); this reduced P200 effect was interpreted as reflecting inhibited phonological processing by the non-homophonic radical embedded in the irregular target character. Consistent with these accounts, the enhanced P200 effect in our study may reflect faster and sustained phonological activation of high consistency characters than of low consistency characters during the radical-based bottom-up process.

4.3.3 N400

Our main finding regarding the central-parietal N400 is that high consistency characters elicit a smaller N400 in the left hemisphere and midline areas than low consistency characters.

The N400 is associated with lexical and semantic processing (for reviews, see Kutas & Federmeier, 2011; Lau et al., 2008). In general, there are two accounts regarding the N400 effect, which are not mutually exclusive. The lexical view of the N400 effect suggests that it reflects facilitated activation of semantic features of the long-term memory representation that is associated with a lexical item (e.g., Kutas & Federmeier, 2000). The integrative view of the N400 effect suggests that it reflects a combinatorial process, integrating information with the working context (e.g., Brown & Hagoort, 1993).

Accordingly, there are two possibilities for the reduced N400 effect for high consistency characters in our study. First, it may reflect facilitated semantic processing from orthography to semantic via phonology due to faster phonological processing of high consistency characters than that of low consistency characters. Meanwhile, it may reflect facilitated integrative process of all lexical information because the phonological information of high consistency characters is more available than that of low consistency characters.

4.3.4 FN400

Consistency interacted with regularity in modulating the FN400 amplitude. High consistency characters induce more negative going FN400 than low consistency characters in Fz and F4 electrode clusters in regular characters only. Similarly, regular characters elicit more negative going FN400 than irregular characters in high consistency characters only.

In prior research, the FN400 was associated with the processing of familiarity information in recognition memory research (e.g., Rugg & Curran, 2007; Rugg et al., 1998): when participants were asked to judge whether the word had been studied or not, the FN400 was sensitive to the accuracy of judgement with correctly recognized studied words showing less negative going FN400 than both new words and misclassified studied words. This view was further supported by studies reporting robust FN400 old/new effects with semantically ‘empty’ items such as abstract visual patterns (Groh-Bordin, Zimmer, & Ecker, 2006) and unfamiliar faces (Curran & Hancock, 2007). However, some other studies (e.g., Voss & Federmeier, 2011) found that FN400 was also associated with conceptual priming, arising from the processing of the stimuli's semantic information.

One noticeable thing in our results is that the observed consistency and regularity effects on FN400 show the same pattern, an enhanced FN400 effect: High consistency characters induced more negative going FN400 than low consistency characters; regular characters elicited more negative going FN400 than irregular characters. These enhanced FN400 effects of consistency and regularity may reflect that the two factors operate similarly in certain processes. In our view, this enhanced FN400 effect reflects interference from a character's friends (in high consistency characters) or its homophonic phonetic radical (in regular characters) during the top-down processes following the activation of the host character's phonological representation. For a high consistency character, when the character itself is of low frequency, the character-based identification may be not rapid enough to stabilize the connection between its orthographic and phonological representation. Instead, because the character has high frequency friends/phonetic radicals, the radical-based identification could activate its phonological representation rapid enough to initiate top-down process. The top-down process from the host character's phonological representation may activate the orthographic representation of the character's high frequency friends or phonetic radical, producing interference to the orthographic activation of the character itself. In other words, a character's friends and phonetic radical may interfere with the orthographic processing of the character. The interaction between consistency and regularity suggests that the two factors may operate jointly at certain stage. Therefore, our accounts align more with the view that the familiarity related FN400 can be modulated by perceptual information processing (i.e., orthographic selection in our case), not by semantic processing.

4.3.5 LPC

Our main finding regarding the LPC is that consistency interacts with regularity in modulating the LPC amplitude. High consistency characters elicit more positive going LPC than low consistency characters in regular characters only.

In prior research, LPC had been associated with memory retrieval from episodic memory (e.g., Rugg et al., 1998), the updating of working memory with information retrieved from long-term memory (e.g., Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991), and conscious recollection of the prime-target relationship (e.g., Bouaffre & Faïta-Ainseba, 2007; Meade & Coch, 2017). For instance, in the study of Rugg et al. (1998) on recognition memory, words that are later remembered are associated with more positive going LPC than words that are forgotten and this LPC effect has been interpreted as reflecting conscious recollection of studied words from episodic memory. In the study of Petten et al., (1991), repeated words in discourse reading elicit less positive going LPC than control words, and this repetition-related LPC effect is proposed to be associated with the updating of working memory with information retrieved from long-term memory.

In our study, the LPC effect by consistency may be related to the task demand for homophone judgement because participants need to maintain the phonological information in working memory after recognizing the target character. Specifically, the enhanced LPC effect may reflect that high consistency characters are easier to maintain than low consistency characters. However, this LPC effect by consistency is restricted to regular characters only. It is possible that at this stage, participants may detect the congruence between the host character and its phonetic radical, and the phonetic radical of regular characters may draw more attention than that of irregular characters, which make the consistency effect more prominent in regular characters.

4.4 Why does consistency play a more important role than regularity in character recognition?

Our study demonstrates that consistency plays a dominant role in Chinese character recognition by finding robust and persistent impacts of consistency on the pronunciation transcription task and ERP responses during covert naming. This is further supported by another experiment (Zhou and Perfetti, in preparation), which shows that it is the consistency of characters, not the regularity, that plays a dominant role in modulating the phonological interference effects on ERPs in meaning judgement task. Behaviorally, the phonological interference effects are the findings that in the semantic judgement task, homophonic character pairs, which are not semantic related, take longer time to reject than control (non-homophonic) pairs (Perfetti and Zhang, 1995). Electrophysiologically, we found that, only when the target (second) characters were of high consistency, were phonological interference effects (the difference between homophone condition and control condition) observed on the P200 (enhanced) and N400 (reduced) components. These results lead us to ask why consistency plays a more important role than regularity in character recognition.

The question becomes clearer if we consider the fundamental difference of the two factors. The consistency of Chinese characters reflects the extent of global congruence between a character and its orthographic neighbors; in other words, the consistency reflects the statistical distribution of orthography-to-phonology mappings of Chinese characters. By contrast, the regularity of Chinese characters reflects only the local congruence of a character with its phonetic radical. The dominant role of consistency suggest that skilled readers learn the statistical distribution property of orthography-to-phonology mappings of a script across years of reading experience. This is also consistent with the research that suggests statistical learning mechanism of our cognitive systems during learning and information processing (e.g., Frost, Armstrong, Siegelman, & Christiansen, 2015).

The use of “regularity” in Chinese is somewhat misleading as an analogy to alphabetic writing, where the idea of a “rule” (correctly or not) implies a distinction between regular (rule-following) and irregular (rule-violating). Also, the way in which regularity of English works, i.e., assembling phonemes, does not apply to Chinese reading. Because of these, the concept of validity rather than regularity has been occasionally applied to Chinese (Perfetti, Zhang, & Berent, 1992; Zhang, Perfetti, & Yang, 2000): Validity describes whether the phonetic radical is a valid cue to the pronunciation of the character or not. Thus, regularity does not serve well as a universal descriptor of orthography to phonology mappings.

However, it is possible to capture the more universal aspects of orthography-to-phonology mappings by considering two relevant dimensions that can apply across languages (see Table 4). The first dimension is global versus local, which applies to the distinction between consistency and regularity. Consistency reflects the global level (usually multiple units) congruence among orthographic neighbors across the whole lexicon; regularity reflects the local level (specifically two units) congruence between a lexical unit and a single sublexical unit. The second dimension is part versus whole, which applies to the language 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), whereas that of English is a part-to-whole mapping (i.e., from a phoneme/word body to a syllable).

Table 4. Comparisons on consistency and "regularity" between Chinese and English

	"Regularity"	Consistency
English	**Local** small grain (**phoneme**) congruence	**Global** large grain (**word body**) congruence
Chinese	**Local** same grain (**syllable**) congruence	**Global** same grain (**syllable**) congruence

One might argue against the "local" nature of regularity of English because the sublexical units of English, i.e., 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 grapheme to a give 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 (Colheart et al., 2000). In a more recent extended DRC model (Pritchard, Coltheart, Marinus, & Castles, 2016), a GPC rule learning algorithm has been implemented to learn the statistical distribution of orthography to phonology mappings. So GPC rules operate locally, but have their computational properties derived globally.

In this reframed picture, the consistency of Chinese and that of English are similar in that both reflect global level mapping congruence, while differing in their grain size (see Table 5). This distinction may be captured directly by PDP models because they learn written English's statistical distribution properties at both word body level and phoneme level. In other words, the grain size of the statistical distribution properties of a script's spelling sound mappings seems to not matter in these models. Thus, consistency seems to serve well as a universal descriptor of orthography to phonology mappings.

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