Validation of constituent logographemes and radials in Chinese characters using handwriting data

Dustin Kai-Yan Lau
Hong Kong Polytechnic University

Correspondence to be address to Dustin Kai-Yan Lau, Department of Chinese and Bilingual Studies, Hong Kong Polytechnic University, Hong Kong SAR (email: dustin.lau@polyu.edu.hk). Telephone number: (852) 3400-3636

Abstract

Studies have shown that logographemes and radicals, sub-character units in Chinese characters, are represented in the orthographic lexicon and are functional processing units in writing Chinese characters. Nevertheless, there is no consensus regarding how characters should be segmented into logographemes and radicals. This article reports the handwriting data of a list of 209 Chinese characters (95 non-phonetic compounds and 114 phonetic compounds) in a copying task. To validate the constituent logographemes and radicals of the target Chinese characters, comparisons among between-radicals-inter-stroke intervals (ISI), between-logographemes-ISI, and within-logographeme-ISI, as well as their interactions with orthographic factors, including character frequency, stroke numbers and configurations, were conducted using factorial analyses. Results showed that the ISI comparison method is effective in validating the constituent logographemes and radicals in Chinese characters. Based on this list of 209 stimuli, another 1227 Chinese characters sharing the same set of radicals with the stimuli were further identified. Their constituent logographemes were deduced accordingly. Altogether the over 1000 Chinese with validated constituent logographemes will serve as a powerful reference for future psycholinguistic and neurolinguistics research. Future potential applications were discussed.

Keywords: Database, Chinese, Radicals, Logographemes

Background

It has long been the goal among psycholinguistic researchers to understand how people write words. By investigating the word writing process, the storage and processes of the orthographic, phonological and semantic information of words in the lexicon can be deciphered. Studies in alphabetic orthographies documented the use of sublexical units such as digraphs (Tainturier & Rapp, 2004), syllables (Caramazza & Miceli, 1990), and morphemes (Schiller, Greenhall, Shelton, & Caramazza, 2001) as functional writing units. Similarly, psycholinguistic studies in non-alphabetic orthographies, like Chinese, also documented the use of sublexical units as functional writing units, with some cross-linguistic differences (e.g. Law & Leung, 2000).

In the last two decades, sizeable number of experiments were conducted to explore the processing in writing Chinese. By observing the writing errors produced by brain-damaged patients, these studies have advanced our understandings of the lexical processing in writing Chinese, including the hypothesis of structural representations of Chinese graphemes that include characters, radicals and logographemes (Han, Zhang, Shu, & Bi, 2007; Law & Leung, 2000; Law, Yeung, Wong & Chiu, 2005). However, there is currently no consensus regarding the definition of the constituent radicals and logographemes in Chinese characters among published studies (e.g. Xing, 2005; Lui, 2012). The aim of the current study is to explore the possibility of using handwriting experiments to validate the radical and logographeme boundaries in Chinese characters.

The Chinese writing system is morpho-syllabic, where each Chinese character usually corresponds to one syllable and one morpheme (Hoosain, 1992). Basically, each Chinese character is a compilation of strokes organized in a square construction. For example, the character “下” corresponds to the syllable [haa6][1] and the morpheme <down> and is constructed by putting the three strokes “一”, “丨” and “丶” in a specific pattern. There exists a major group of characters in Chinese called phonetic compounds, which are composed by combining semantic radicals that give clues to meanings and phonetic radicals that give clues to sound. For example, the character “枝” [zi1] <twig> contains the semantic radical “木” <wood> that gives clues related to the character meaning and the phonetic radical “支” [zi1] <support> that gives clues to related to the pronunciation of the character. The role of radicals in character recognition has been reported in plenty of studies (e.g. Feldman & Siok, 1999; Lau, Leung, Liang & Lo, 2015; Law & Wong, 2005; Zhou & Marslen-Wilson, 1999). In general, higher accuracy and shorter latency were observed in the processing of regular characters, those that share the same syllables with their phonetic radicals, than irregular characters.

Radicals also play significant role in Chinese character writing. For example, Law, et al. (2005) tested a Chinese dysgraphic patient using tasks of writing-to-dictation and written-naming. They reported that the patient produced errors that involve substitutions, additions and deletions of strokes, phonetic radicals or semantic radicals. They suggested that the results indicate that apart from strokes, phonetic and semantic radicals are involved as functional processing units in the writing process. However, in another study, Law and Leung (2000) reported a Chinese dysgraphic patient produced writing errors that involve substitutions of sub-radical units called logographemes (stroke patterns in radicals that are spatially separated, e.g. “十” and “又” in the radical “支”). In another study by Han, et al. (2007), another stroke patient produced similar errors of logographeme substitutions,

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[1] This current study was conducted in Hong Kong where traditional Chinese characters and Cantonese were used. In this paper, phonetic transcriptions are represented in *jyutping,* a romanisation system developed by the Linguistic Society of Hong Kong.

deletions and transpositions. These authors, therefore, concluded that besides radicals and strokes, logographemes are also functional processing units in writing Chinese characters. Since all dysgraphic patients were observed to produce writing errors with all units (strokes, logographemes and radicals), it is, in general, agreed that orthographic units with different sizes are organized in the orthographic representations at the same level in the mental lexicon (Law et al., 2005) and are all involved in the writing process.

Nevertheless, replicating the above results among normal individuals' writing is difficult if not impossible. Current research of Chinese writing relies heavily on observations of errors produced by individuals to infer the functional writing units used by them. As normal people seldom make errors in their writing, it is not possible to infer the functional writing units used by them. Besides, because normal people seldom make errors in frequently occurring stimuli, it is not possible to identify the functional writing units by asking them to write frequently occurring stimuli. Instead, less frequently occurring stimuli have to be used. However, the use of less frequently occurring stimuli does not only limit the generalizability of the results but may also yielded unwanted results as substitutions of homophonous characters may occur. This makes analysis of the written outcome of the target characters impossible. Finally, even if errors are successfully observed from some participants, it is still unclear whether they came from the normal processing of writing or they only reflected the use of compensatory strategy in fulfilling the writing task requirements.

Using an experimental design, Chen & Cherng (2013) attempted to detect the use of logographems and radicals in Chinese character writing among normal individuals. They arranged characters with shared first strokes, shared first logographemes, or shared first radicals into three "homogeneous" groups and characters without shared components into another three "heterogeneous" groups. They observed that in the written version of the form preparation task using either the homogeneous or heterogeneous group of stimuli, their participants showed shorter response time in writing characters in the shared logographemes and shared radicals homogeneous groups than their corresponding heterogeneous groups. Comparable response time was observed in the shared strokes homogeneous group and its corresponding heterogeneous groups. Clearly, the results by Chen & Cherng (2013) supported the notion that logographemes and radicals, instead of strokes, are functional writing units in Chinese character writing. Nevertheless, Chen & Cherng (2013) also highlighted the issue of operational ambiguity regarding the current definition of logographemes.

Xing (2005) and Xing & Shu (2008) documented a list of “basic components” of Chinese characters. Although the representativeness of the list of over 500 components is supported by the fact that they were identified in primary school Chinese textbooks, the overlapping components within the list were concerned. For example, the items “⺈”, “罒”, “豕”, and “象” are all included in the list as “basic components” of Chinese characters. It is obvious that the former three are sub-components of the last component “象”. If the component “象” is considered the “basic” component, it seems unreasonable that it can be further broken down into other “basic” components. Such overlapping in the contents is one of the major source of the operational ambiguity of the definition of logographemes.

Lui, Leung, Law & Fung (2010) offered another list of 249 logographemes, also extracted from Chinese characters in primary school Chinese textbooks. The logographemes were identified according to the three major criteria of “(1) spatial separation of components, … (2) replaceability of components, … and (3) frequency of co-occurrence of components among characters (pp.10)”. This list has an advantage over the list given by Xing (2005) and Xing & Shu (2008) that overlapping components were largely reduced. For example, the item “象” was not in their list but was broken down into “⺈”, “罒”, and “豕”. One potential problem associated with their list, however, is that the logographemes identified were not validated using empirical writing data. That is, it is unclear whether people will break down the item “象” into “⺈”, “吅”, and “豸” as proposed in the list when they write the item “象”. One possible solution is to obtain writing data to validate the contents in the list.

By obtaining handwriting data from large group of participants, studies have successfully detected people’s use of orthographic units of various grain size in writing (e.g. Kandel, Alvarez, & Vallée, 2008; Kandel, Hérault, Grosjacques, Lambert, Fayol, 2009). For example, by measuring the inter-letter intervals (ILI) in a multi-morphemic word copying task, Kandel, et al. (2008) observed that within-morpheme-ILIs were shorter than between-morphemes-ILIs. They suggested that the results indicated the participants’ use of morphemes as processing units in writing. In another handwriting study using a multi-syllabic word copying task, Kandel, et al. (2009) observed that the peak letter stroke durations in participants’ handwriting were located at the syllable boundaries. Similarly, the results were suggested to be indicating participants’ use of syllables as processing units in writing.

Handwriting studies have also been applied in the search of functional processing units in writing Chinese (Chu & Lau, 2017; Lau, Ha & Law, 2016). Lau, et al. (2016) created pseudo-characters by combining semantic and phonetic radicals in their legal positions and instructed school-aged participants to copy the pseudo-characters using a wireless pen in the form of a capacitive stylus on the screen of a tablet. The tablet recorded the durations and positions (coordinates) each time the capacitive stylus touched and left the screen. The inter-stroke intervals (ISI) and inter-stroke distance (ISD) were calculated accordingly. For example, Figure 1 illustrates the strokes labeled A to L of the character 結. A_0 indicates the starting position of the stroke A and A_1 indicates its ending position; B_0 indicates the starting position of the stroke B and B_1 indicates its ending position, and so on. In their study, Lau, et al. (2016) compared the ISI between radicals, i.e. between F_1 and G_0 in the given example, the ISI between logographeme, i.e. between C_1 and D_0 and between I_1 and J_0 in the given example, and the ISI within logographemes, e.g. between A_1 and B_0, or between K_1 and L_0 in the given example. They reported that ISIs between radicals were significantly longer than ISIs between logographemes which were significantly longer than ISIs within logographemes after controlling for ISD. They suggested that the longer between-units ISIs were due to longer processing time for planning and/or retrieval of subsequent writing unit(s). In a similar developmental study by Chu & Lau, (2017), an identical copying task was used but pseudo-characters were created by combining either high or low frequency radicals according to graphotactic rules. They reported that after controlling for ISD, between-radical ISIs were longer than within radical ISIs in both high and low frequency conditions. In addition, they also reported that between-radical ISIs in the high frequency condition were longer than between-radical ISIs in the low frequency condition while within-radical ISIs were not affected by radical frequency. The significant interactions between radical frequency and ISI locations further supported that the longer between-units ISIs were driven by processing of orthographic units instead of merely visual-motor processes. Altogether, the results of these studies confirmed that handwriting studies, originally believed to be reflecting only peripheral processing of writing (Ellis & Young, 1996), are capable of capturing the central processing of writing as well.

Figure 1 about here

Therefore, the aim of the current study is to examine the possibility of validating the constituent radicals and logographemes in Chinese characters using handwriting data. The product of the database should be an invaluable tool for future psycholinguistics and neurolinguistics studies.

Method

Stimuli

A total of 211 traditional Chinese characters were chosen. These consisted of 95 non-phonetic compounds (nonPC) and 116 phonetic compounds (PC) selected from the Hong Kong Corpus of Chinese NewsPapers (HKCCN) (Leung & Lau, 2010). Details of the nonPC and PC were given in Appendix A and Appendix B respectively. There are 6866 different traditional Chinese characters in the HKCCN, which consist of 123677 news articles published by the eight most popular newspaper publishers in Hong Kong. The 211 target characters were selected because they contain only unambiguous logographeme and radical boundaries, i.e. all the logographemes and radicals are non-superimposed[2] in these characters. The following lexical and sublexical variables of the selected characters were also derived from the HKCCN.

Character frequency. The effect of character frequency on Chinese lexical processing has been widely reported. High frequency characters usually yielded quicker responses in experimental tasks such as naming (e.g. Lee, Tsai, Su, Tzeng & Hung, 2005), lexical decision (e.g. Sze, Liow & Yap, 2013), and writing-to-dictation (e.g. Delattre, Bonin & Barry, 2006). In the current study, character frequencies are compiled from the HKCCN. There are approximately 7.6 million characters in the HKCCN. Character frequency value of each of the target items refers to the counts of appearance of the character per million.

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[2] In the original list proposed by Lui, et al. (2010), some characters were chunked based on logographemes superimposed on each other, e.g. 東 was chunked into 木 and 日. These characters were not selected in the current study because the between-units-ISIs can be very ambiguous in these stimuli. More will be discussed about this group of characters in the Discussion.

PC vs nonPC. A considerable amount of studies has demonstrated the role of semantic radicals (e.g. Feldman & Siok, 1999) and phonetic radicals (e.g. Zhou & Marslen-Wilson, 2000) in the processing of PC. In the current study, characters are categorized as either PC or nonPC according to the HKCCN. The HKCCN categorized characters into PC or nonPC based on the dictionary Shuowen Jiezi Zhu (Xu, 1963), which documented the origins of individual characters.

Configuration. Semantic and phonetic radicals in Chinese characters are usually combined in different spatial arrangements, or configurations. According to Fu (1993), up to 10 different configurations were identified, such as horizontal (e.g. 清), vertical (e.g. 完) and semi-enclosed configuration (e.g. 速). Previous studies have suggested that character configuration plays a significant role in Chinese character recognition (e.g. Yeh & Li, 2002). In this current study, PC having semantic and phonetic radicals arranged in horizontal or vertical configurations were selected. Altogether, there are 65 horizontally configured PCs and 43 vertically configured PCs in the target list.

Radical and Logographemes boundaries. The radical and logographeme boundaries of the selected PCs in the current study were defined according to HKCCN. As stated in the above, semantic and phonetic radicals of PCs in the HKCCN were coded according to (Xu, 1963), therefore, radical boundaries were defined accordingly. In the HKCCN, logographemes of characters were coded according to Lui, et al. (2010). According to Lui (2012), there were ambiguity in their process of logographeme identification, particularly when one identified logographeme superimposed on another logographeme. Among all the selected characters in this current study, there exists no superimposed logographemes to ensure they have unambiguous radical and logographeme boundaries.

Stroke numbers. The role of number of strokes in Chinese character recognition is controversial. For example, Leong, Cheng and Mulcahy (1987) reported that both skilled and less skilled Chinese readers responded quicker to characters with fewer strokes than characters with many strokes in speeded naming and lexical decision tasks. On the other hand, in the megastudy by (Liu, Shu & Li, 2007), effect of number of strokes on character naming was not significant. Nevertheless, the factor of number of strokes was included in the current study to explore its role on Chinese character writing. Selected items were first ranked according to their number of strokes in ascending order. Items in the upper and lower third in the lists were identified as characters with many strokes and characters with few strokes respectively. Among the targets, the number of strokes of characters with many strokes ranged from 3 to 8 and the number of strokes of characters with few strokes ranged from 10 to 18.

Table 1 summarized the mean character frequency and mean number of strokes of each factorial comparison conducted in this study.

Table 1 about here

Participants

A total of 20 right-handed undergraduate students (gender-balanced, mean age = 22.4 years, S.D. = 1.8) with normal, or corrected-to-normal, vision were recruited. All participants were native Cantonese speakers born and received mainstream education in Hong Kong. None of the participants reported to have history of cognitive, learning, or motor problems.

Procedure

A direct copying task was used. Each participant was instructed to use one tablet and one stylus pen in the copying task. Two pre-experimental training trials on using the stylus pen to write on the tablet were conducted to ensure that the participants knew how to manage the pen and tablet. In each of the randomly ordered experimental trial, a target character was displayed and the participants were required to directly write down the presented character on the tablet screen using the stylus pen. The participants were instructed to write each stroke precisely by avoiding merging successive strokes. The elapsed time and coordinates each time the stylus pen touched or left the tablet screen were recorded accordingly. The duration of the whole experiment was about 15 minutes.

Measures

The ISI and the corresponding inter-stroke-distance (ISD), calculated based on the coordinates where the stylus pen left and retouched the table screen were obtained. The ISIs (and the corresponding ISDs) were then categorized into different boundary types (between-radical-ISIs, between-logographeme-ISIs and within-logographeme-ISIs) according to the positions they occurred in the writing process. Finally, the entire writing process and the final written output was also obtained.

Data analysis

nonPC. A 2 (Boundary Type) x 2 (Stroke Number) ANCOVA and a 2 (Boundary Type) x (Character Frequency) ANCOVA using the mean ISI of each item as the dependent variable and mean ISD of each item as the covariate were calculated.

PC. A 3 (Boundary Type) x 2 (Configuration) ANCOVA, a 3 (Boundary Type) x 2 (Stroke Number) ANCOVA and a 3 (Boundary Type) x 2 (Character Frequency) ANCOVA using the mean ISI of each item as the dependent variable and mean ISD of each item as the covariate were calculated.

Because there exists more within-logographeme data than between-logographemes and between-radicals data, random sampling was conducted on the within-logographeme data to ensure equal group size before conducting the ANCOVA test. Post-hoc analysis using Bonferroni post hoc tests were calculated when any of the main and/or interaction effects were significant.

Results

Two PC items, “菊” and “糜” were excluded from the analysis because over 10% of the participants used stroke sequence that crossed the logographeme boundaries, i.e. they wrote “米” using the sequence 十 → 丷 → 八, instead of the 丷 → 木 suggested by Lui, et al. (2010). The different stroke sequences observed across participants probably suggested that they (1) do not segment the “米” into logographemes or (2) do not consistently segment the logographemes in “米” in the same way. In the rest of the items, no more than 5% of the participants used stroke sequence that crossed the logographeme boundaries. Data from items with stroke sequence crossing the logographeme boundaries (a total of 0.7%) and ISIs beyond three standard deviations from the mean (a total of 0.9%) were excluded from the analysis.

nonPC

Table 2 summarized the within- and between-logographems ISIs after controlling for ISDs of characters with many strokes and characters with few strokes. Results of ANCOVA revealed significant main effect of Boundary Type [F (1, 133) = 35.51, MSE = .047, p < .0001][3] and significant main effect of Stroke Number [F (1, 133) = 7.692, MSE = .010, p = .006] after controlling for ISDs. Between-logographemes ISIs were longer than within-logographeme ISIs after controlled for ISDs. Interaction effect between Boundary Type and Stroke Number was also significant [F (1, 133) = 9.36, MSE = .012, p = .003]. Results of

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[3] Altogether, five ANCOVA tests were conducted. Therefore, a more stringent critical value of 0.05/5 = 0.01 will be used as reference for detection of statistical test significance.

post-hoc analysis showed that Between-logographemes ISIs among characters with many strokes were significantly longer that Between-logographemes ISIs among characters with few strokes (*p* = .004). Within-logographemes ISIs were comparable between characters and many strokes and characters with few strokes.

Table 2 about here

Table 3 summarized the within- and between-logographems ISIs after controlling for ISDs of high and low frequency characters. Results of ANCOVA revealed significant main effect of Boundary Type [F (1, 189) = 57.09, MSE = .072, *p* < .0001] and significant main effect of Character Frequency [F(1, 189) = 23.09, MSE = .029, *p* < .001] after controlling for ISDs. Between-Logographeme ISIs were longer than within-logographeme ISIs and ISI of high frequency characters were longer than ISI of low frequency characters after controlling for ISD. Interaction effect between Boundary Type and Character Frequency was also significant [F(1, 189) = 13.69, MSE = .017, *p* < .001]. Results of post-hoc analysis showed that Between-logographemes ISIs among low frequency characters were significantly longer than Between-logographemes ISIs among high frequency characters (*p* < .001). Within-logographemes ISIs were comparable between high and low frequency characters.

Table 3 about here

PC

Configuration

Table 4 summarized the within-logographeme-, between-logographems- and between-radical-ISIs after controlling for ISDs of horizontally- and vertically-configured characters. Results of ANCOVA revealed significant main effect of Boundary Type [F (2, 297) = 69.57, MSE = .069, $p < .0001$] after controlling for ISDs. Results of post-hoc analysis showed that Between-Radical ISIs were longer than Between-Logographeme ISIs, which in turn were longer than within-logographeme ISIs after controlling for ISDs ($p < .001$). Main effect of Configuration and interaction between Boundary Type and Configuration were not significant ($p >.1$)

Table 4 about here

Many strokes vs few strokes

Table 5 summarized the within-logographeme-, between-logographems- and between-radical-ISIs after controlling for ISDs of characters with many strokes and characters with few strokes. Results of ANCOVA revealed significant main effect of Boundary Type [F (2, 248) = 78.33, MSE = .058, $p < .0001$] and significant main effect of Strokes Number [F(1, 248) = 10.40, MSE = .007, $p = .001$] after controlling for ISDs. Results of post-hoc analysis showed that Between-Radical ISIs were longer than Between-Logographeme ISIs, which in turn were longer than within-logographeme ISIs after controlling for ISDs. Besides, ISI of characters with many strokes were longer than ISI of characters with few strokes after controlled for ISD. Interaction effect between Boundary Type and Strokes Number was also significant [F(2, 248) = 5.11, MSE = .004, $p = .003$]. Results of post-hoc analysis showed that Between-Radical ISIs and Between-logographemes ISIs among characters with many strokes were significantly longer than their counterparts among characters with few strokes respectively ($p = .001$ and $p = .003$ respectively). Within-logographemes ISIs were comparable between characters with many strokes and characters with few strokes.

Table 5 about here

High frequency vs Low frequency

Table 6 summarized the within-logographeme-, between-logographems- and between-radical-ISIs after controlling for ISDs of high and low frequency characters. Results of ANCOVA revealed significant main effect of Boundary Type [F (2, 329) = 71.90, MSE = .125, *p* < .0001] and significant main effect of Character Frequency [F(1, 329) = 32.37, MSE = .056, *p* < .0001] after controlling for ISDs. Results of post-hoc analysis showed that Between-Radical ISIs were longer than Between-Logographeme ISIs, which in turn were longer than within-logographeme ISIs after controlling for ISD. Besides, ISI of low frequency characters were longer than ISI of high frequency characters after controlled for ISD. Interaction effect between Boundary Type and Character Frequency was also significant [F(2, 321) = 12.56, MSE = .022, *p* < .001]. Results of post-hoc analysis showed that Between-Radical ISIs and Between-logographemes ISIs among low frequency characters were significantly longer than their counterparts among high frequency characters respectively (*p* < .001). Within-logographemes ISIs were comparable between high and low frequency characters.

Table 6 about here

Discussion

The aim of the current study is to verify the possibility of applying the method of comparisons of between-units-ISI and within-unit-ISI to validate the constituent logographemes and radicals in Chinese characters. Participants were invited to copy nonPC and PC characters on an Android tablet and handwriting data were obtained accordingly. Results from the nonPC copying showed longer between-logographemes-ISI than within-logographeme-ISI after controlling for ISDs. Similarly, results from the PC copying showed longer between-radical-ISI than between- and within-logographeme-ISI as well as longer between-logographeme-ISI than within-logographeme ISI after controlling for ISDs. The longer between-units ISIs were attributed to the time required for retrieval and/or planning of the constituents and the stroke sequences of the successive writing units (Chu & Lau, 2017; Kandel, et al., 2008; Lau, et al. 2016). Therefore, the results were consistent with previous reports that people use radicals and logographemes as functional processing units in writing Chinese characters (Han, et al., 2007; Law & Leung, 2000; Law, et al., 2005).

The insignificant main effect of Configurations and interaction effect between Configuration and Boundary Type observed in the PC copying indicated that after controlling for ISDs, the potential confounding from the longer distance of stylus traveling resulted from different configurations of components within the characters can be avoided. It is important to emphasize that results of the current study did not reject the importance of character configurations in Chinese character writing. Instead, configurations of Chinese characters in the writing process should be indispensable, or characters with similar components, e.g. 易 and 昒, would be confused with each other. However, it is hypothesized that the configurations of characters should be retrieved before the implementation of the handwriting processes. Using the examples given, the horizontal and vertical configurations predefine the position of the first stroke and the size of the logographemes to be written. Otherwise, the output would be distorted.

Ellis and Young (1996) suggested that the architecture of the writing process can be divided in to central and peripheral processing. The central processes involve the orthographic long-term memory, conversion from phonology to orthography, and orthographic short-term memory. On the other hand, the peripheral processing involves allograph selections, graphic motor pattern selections and graphic motor patterns execution. As illustrated in the above example, to avoid confusions among characters with similar components, configurations of Chinese characters should be stored in the orthographic long-term memory, hence processed in the central processing of writing. The handwriting production observed in the current study, on the other hand, should reflect more on the peripheral processing instead. This explains the insignificant main effect of Configurations in observed.

Another important finding of the current study is the significant effect of number of strokes on Chinese character handwriting. Results showed longer between-units-ISI among characters with many strokes than between-units-ISI among characters with few strokes, in both nonPC and PC copying. On the other hand, within-units-ISI among characters with many strokes were comparable to within-units-ISI among characters with few strokes, in both nonPC and PC copying. There are two possible explanations for this observation. First, it may be possible that writing units with more strokes require longer retrieval and/or planning time. However, to the author's knowledge, there is a lack of previous reports to support this explanation. More work on the effect of stroke number and character writing is needed to warrant this. Alternatively, a more probable explanation is that the longer between-units ISIs associated with writing units with more strokes are related to the orthographic output buffer (Caramazza, Miceli, Villa, & Romani, 1987; Han, et al., 2007) in the writing process. The orthographic output buffer temporarily stores orthographic units output from the orthographic lexicon while the units are pending for motor execution in handwriting (Caramazza, et al., 1987). In a French study using words with different syllable length in a copying task, Lambert, Kandel, Fayol, & Espéret (2008) observed that writing latencies were modulated by number of syllables in words. They suggested that the longer latencies associated with words with more syllables were attributed to the increased demand due to more processing units temporarily stored in the orthographic output buffer. Han, et al. (2007) suggested that logographemes are the functional units temporarily stored in the orthographic output buffer in the case of Chinese character writing. In the current study, since characters with many strokes also contain more logographemes than characters with fewer strokes ($p < .001$ for both PC and nonPC), it is possible that the more logographemes in characters with many strokes resulted in increased demand in the orthographic output buffer in the task. Hence, longer between-units ISIs were observed. The comparable within-unit-ISI across different conditions also indicated that once the retrieval and/or planning was completed, the motor execution within the writing units would not be affected.

Nevertheless, the effect of stroke number on Chinese character processing is controversial. Although some studies reported its significance in Chinese character recognition and attributed it as an indicator of visual complexity (Leong, et al. 1987), others reported no significant effect of stroke number on character recognition (e.g. Liu, et al. 2007). Su and Samuels (2010) suggested that the discrepancies could be due to different frequency ranges of the stimuli used in different studies. Another possible confounding factor is the age-of-acquisition of the stimuli. As indicated in the large-scale study by Liu et al. (2007), number of strokes of characters correlated significantly with age of acquisition. Characters with fewer strokes tend to be learnt earlier than characters with more strokes, in elementary classrooms in which intensive copying practice were emphasized (Liu, et al. 2007). All of these confounding factors make verifying the effect of stroke number on Chinese character processing difficult. Nevertheless, the results obtained in the current study involving character encoding may also indicate that stroke number has a stronger effect on character encoding, as both central and peripheral processing are involved, than character decoding.

Future large scale studies that include more items and other psycholinguistic measures such as age of acquisition ratings will be needed to verify this.

Finally, significant effect of Character Frequency on Chinese character handwriting was observed in the current study. Results showed longer between-units-ISI among low-frequency characters than between-units-ISI among high-frequency characters, in both nonPC and PC copying. On the other hand, within-units-ISI among high- and low-frequency characters were comparable, in both nonPC and PC copying. The longer pauses between writing units in the low-frequency condition than the high-frequency condition suggested that the time required for retrieval and/or planning of the constituents and their stroke sequences of the low-frequency writing units is longer than that of high-frequency writing units. Similar orthographic frequency effect on handwriting were reported before (e.g. Chu & Lau, 2017; Lambert et al. 2008). This finding is also consistent with the notion of cascaded relationship between the central processing and peripheral processing of writing (e.g. Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013).

Altogether, the interactions between boundary types and different orthographic factors including character frequency and complexity confirmed that the significant results in the ISI comparisons were driven by orthographic processing instead of mere visual motor processing.

The current study made the first attempt to validate the constituent logographemes and radicals of the target Chinese characters by using handwriting measures. The significant difference between-units ISIs and witin-units ISIs indicated that people showed tendency to spend longer pauses between logographemes and between radicals in handwriting. The significant frequency effect stroke number effect observed further supported that the longer pauses observed were driven not only by peripheral but also central processing of Chinese character writing. However, there are methodological and theoretical issues that needs to be addressed.

First of all, methodologically, a more stringent and ideal validation process should be conducting the ISI comparison on each individual item instead of conducting the group analysis used in the current study. There would be, however, the concern of statistical power if individual item analyses were to be conducted. Conducting 209 ANCOVA analysis means that in order to avoid Type I error, a lot more participants have to be involved in copying each item so as to fulfil even the minimal critical value required after the corrections due to multiple comparisons. Even if this can be fulfilled, however, the chance of making Type II error by accepting only the minimal critical values of 209 ANCOVA tests would also be increased. Therefore, conducting individual item analyses may be not be feasible unless very big data is collected. It is suggested that future studies using recent trend of crowdsourcing research paradigm (e.g. Huang, Wang, Yao & Chan, 2016) should be considered to achieve a more ideal validation of the set of constituent logographemes tested in the current study.

Next, theoretical concerns need to be addressed. In the current study, separate analyses were conducted on PC and nonPC. One of the reasons is that it is unsure whether the encoding of PC and nonPC are identical or not. Another, yet more important, reason is that defining “radicals” in nonPC can be difficult. In the current study, the term “radical” has been used specifically to represent only phonetic radicals, which give clues to sounds of phonetic compound characters, and semantic radicals, which give clues to meaning of phonetic compound characters. Hence, in the nonPC condition, there is no between-radicals ISIs identified as according to definition, phonetic and semantic radicals only exist in PC. Further studies will be needed to determine if the processing of PC and nonPC are different and whether the processing of semantic and phonetic radicals is different from that of logographemes. If the processing of semantic and phonetic radicals is different from that of logographemes, it will be reasonable to assume that the processing of PC and nonPC should be different, and vice versa.

Another theoretic issue concerns the definition of logographemes. In the current literature, there exists an ‘operational ambiguity (p.6)’ (Chen & Cherng, 2013) of the definition of the terms “bujian”, “stroke clusters”, and “logographemes”. One major confusion caused by the ambiguity is that some logographemes share the same orthographic forms with radicals (e.g. 亻, 扌) and some even share the same orthographic forms with simple characters (e.g. 又, 山). This usually leads to debates such as whether it is needed to assume hierarchical organization of characters, radicals and logographemes in the mental representations, or whether the radical 亻 and the logographeme 亻 are stored as separate entities in the mental representation. For example, the orthographic unit “目” [muk6] <eyes> in the character “矇” [mung4] <unclear> serves as its semantic radical, which contributes to the meaning of <visually related>. However, the orthographic unit “目” in the character “想” [soeng2] <think>, with phonetic radical “相” [soeng1] <mutual> and semantic radical “心” [sam1] <mind-related>, contributes to neither meaning nor sound. Whether or not the “目” in “矇” and the “目” in “想” are separate psychological entities in the lexicon remains unclear.

In fact, the ambiguity does not only exist in Chinese but also in some other languages. For example, Henderson (1985) discussed the issues of lack of clear definition of the word “grapheme” in English, despite its usage in many published studies. With no doubt, the approach of defining graphemes as a set of letters that represent phonemes and the other approach that define graphemes as the minimal functional contrastive unit of a writing system will result in two different sets of graphemes defined. As Henderson (1985) suggested, using stimuli defined with the former approach may have potential risks that graphemes and phonemes, hence orthographic and phonological effects, will not be easily dissociable in experimental studies. Solution to these issues is not simple. A lot more studies in this field of lexical processing will be needed to allow a "better" definition of graphemes.

Potential research application

It is considered that the list of 209 Chinese characters with constituent logographemes validated using handwriting data is an invaluable reference for various psycholinguistic and neurolinguistics research. First of all, the contents of this list can be generalized to other Chinese characters sharing the same constituents. For example, in the current study, the constituent logographemes 夂 and ⺀ of the target nonPC "冬" [dung1] <winter>, and the constituent logographemes 幺, ⺍, 刀 and 巴 of the target PC "絕" [zyut6] <absolute> were validated. Therefore, it is deduced that the constituent logographemes of the character "終" [zung1] <end>, which shared the same semantic radical with the target PC "絕" and contain the nonPC "冬" as its phonetic radical, are 幺, ⺍, 夂 and ⺀. Following this construct, a total of 1227 Chinese characters were identified from the HKCCN. These identified Chinese characters either shared with the PC stimuli the same set of constituent radicals or contained the PC and/or nonPC as their radicals. The constituent component logographemes of these 1227 Chinese characters were deduced from the respective PC and nonPC in the target list of 209 Chinese characters used in the current study. Together with their corresponding frequency of occurrence as indicated in the HKCCN, the list of 1227 characters were given in Appendix C. It is expected that the total 1436 Chinese characters with validated constituent logographemes in the appendices will become invaluable resources for future psycholinguistic and neurolinguistics studies in Chinese.

For example, although studies have documented the significant role of logographemes in writing Chinese characters, its role in character recognition remains unclear. Chua (2014) reported the logographeme frequency effect on lexical decision of Chinese characters over a small group of participants and small number of stimuli. Replications of her results by selecting more items from the list of Chinese characters in the appendices will be possible in the future. The results of these studies will help to verify theories proposed to explain lexical processing in Chinese (e.g. Perfetti, Liu & Tan, 2005; Weekes, Yin, Su & Chen, 2006).

Another potential direction of studies concerns the orthographic development in children. Theories have proposed that development of orthographic representations develop from small units to large units (e.g. Ziegler & Goswami, 2005). However, reports from previous studies in Chinese do not seem to support it (Lau, et al., 2016). One potential reason is the current lack of reference of constituent logographemes of characters that are validated using handwriting data. Using the contents in the appendices, the orthographic development in Chinese can be investigated. Consequently, theories of orthographic development can be substantiated.

In short, the list of characters with valid constituent logographemes should allow researchers to investigate the different roles of logographemes in lexical processing in Chinese which was originally not possible due to the ambiguity of definitions of logographemes in Chinese characters.

Limitation

One limitation of the current set of constituent logographemes of the 1000 characters is that they are all identified from traditional Chinese characters, hence direct application to simplified Chinese characters is very difficult if not impossible. While there are orthographic units shared between simplified and traditional Chinese (e.g. 亻, 刂), it is suggested that a similar handwriting verification study using those characters in the list that are shared in both traditional and simplified Chinese should be conducted. This will help to

Another limitation of the current set of characters with constituent logographemes did not include those with superimposed logographems proposed by Lui, et al. (2010), e.g. 東, 回 and potentially 米. It is suggested that future studies involving these targets with proposed superimposed logographemes will be needed. Although ISI comparisons may not be applicable due to the difficulties of defining between-units ISIs in these items, other handwriting measures, such as writing speed within units, assuming that the writing speed of logographemes of identical orthographic form (e.g. the “木” in “東” and the “木” in “栗”) should be comparable, may be useful in validating these superimposed logographemes proposed.

Conclusion

In summary, the aim of the current study is to investigate if it is possible to validate the database of characters with definitions of radicals and logographemes using handwriting data. The significant longer between-radicals-ISI than between-logographemes-ISI and significant longer between-logographemes-ISI than within-logographeme-ISI observed after controlling for ISD across different conditions confirmed such possibility. Particularly, the significant effects of radical frequency and stroke numbers substantiated that the handwriting data obtained reflected not only peripheral but also central processing of Chinese character writing. Future work will be needed to extend the validated list of logographemes from the current study to other characters not in the list. Finally, the contents of the character list with constituent logographemes and radicals enclosed with the article should also serve as useful resources for future psycholinguistics and neurolinguistics studies.

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Figure 1. Example of (i) inter-stroke intervals (ISI) at logographeme boundary, (ii) ISI at radical boundary, and (iii) ISI within logographeme.

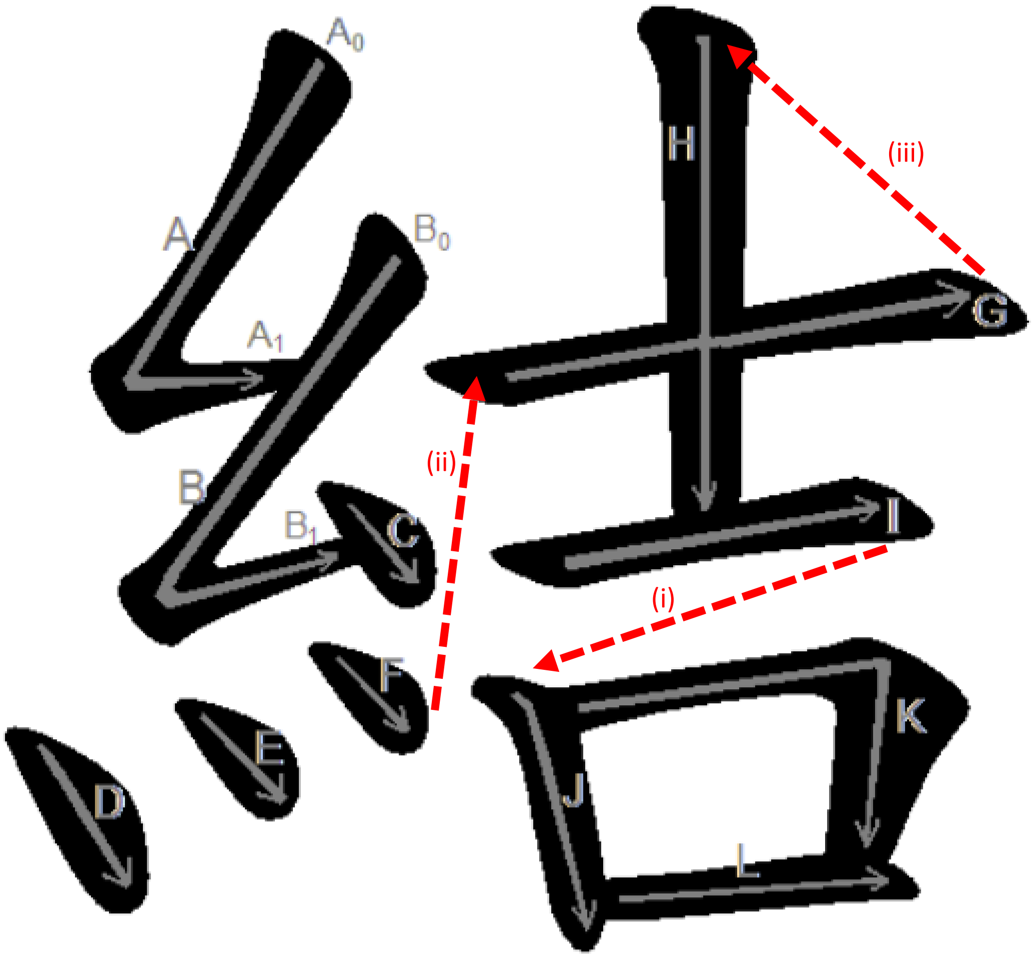

Table 1.

Demographic information of the stimuli in each of the factorial comparisons.

Non-Phonetic compounds

Effect of stroke number

	Many strokes	Few strokes	
N	34	33	
Mean number of strokes (SD)	11.09 (2.08)	5.76 (1.09)	**
Mean character frequency$^{\#}$ (SD)	303.05 (474.85)	510.42 (663.51)	

Effect of character frequency

	High frequency	Low Frequency	
N	55	40	
Mean number of strokes (SD)	8.46 (2.73)	8.49 (2.71)	
Mean character frequency$^{\#}$ (SD)	655.77 (668.74)	31.38 (25.65)	**

Phonetic Compounds

Effect of character configuration$^{\wedge}$

	Horizontal	Vertical	
N	65	43	
Mean number of strokes (SD)	10.11 (2.89)	10.44 (2.82)	
Mean character frequency$^{\#}$ (SD)	317.92 (422.30)	240.47 (416.52)	

Effect of stroke number

	Many strokes	Few strokes	
N	39	36	
Mean number of strokes (SD)	13.02 (1.72)	6.94 (1.19)	**
Mean character frequency$^{\#}$ (SD)	208.17 (510.88)	388.41 (334.49)	

Effect of character frequency

	High frequency	Low Frequency	
N	58	58	
Mean number of strokes (SD)	9.34 (2.77)	11.32 (2.84)	
Mean character frequency$^{\#}$ (SD)	521.08 (473.28)	37.12 (32.75)	**

[#] Frequency values were counted in times/million.

[^] Six characters with semi-enclosing configuration was not included in the analysis because the group size is too small.

[**] $p < .001$

Table 2.

Estimated marginal means of within- and between-logographems ISIs of nonPC with many strokes and nonPC with few strokes.

	Many strokes	Few strokes
Between-Logographeme ISIs (ms)		
Mean	208.43[#]	171.55[#]
Lower bound (95% confidence level)	194.70	158.82
Upper bound (95% confidence level)	222.17	184.28
Within-Logographeme ISIs (ms)		
Mean	143.41[#]	145.35[#]
Lower bound (95% confidence level)	130.25	132.25
Upper bound (95% confidence level)	156.56	158.46

[#] Covariates appearing in the model are evaluated at the following values: ISD = 112.88

Table 3.

Estimated marginal means of within- and between-logographems ISIs of high- and low-frequency nonPC.

	High Frequency	Low Frequency
Between-Logographeme ISIs (ms)		
Mean	174.62[#]	219.57[#]
Lower bound (95% confidence level)	164.97	207.22
Upper bound (95% confidence level)	184.28	231.92
Within-Logographeme ISIs (ms)		
Mean	145.77[#]	151.53[#]
Lower bound (95% confidence level)	135.81	139.72
Upper bound (95% confidence level)	155.73	163.34

[#] Covariates appearing in the model are evaluated at the following values: ISD = 117.54

Table 4.

Estimated marginal means of within-logographeme-, between-logographems-, and between-radicals ISIs of horizontally- and vertically-configured PC.

	Horizontal	Vertical
Between-Radicals ISIs (ms)		
Mean	215.54[#]	217.65[#]
Lower bound (95% confidence level)	205.73	207.84
Upper bound (95% confidence level)	225.35	227.47
Between-Logographemes ISIs (ms)		
Mean	176.91[#]	178.18[#]
Lower bound (95% confidence level)	168.42	167.95
Upper bound (95% confidence level)	185.39	188.41
Within-Logographeme ISIs (ms)		
Mean	151.06[#]	148.04[#]
Lower bound (95% confidence level)	142.66	137.75
Upper bound (95% confidence level)	159.45	158.33

[#] Covariates appearing in the model are evaluated at the following values: ISD = 132.60

Table 5.

Estimated marginal means of within- and between-logographems ISIs of PC with many strokes and PC with few strokes.

	Many strokes	Few strokes
Between-Radical ISIs (ms)		
Mean	225.81[#]	200.49[#]
Lower bound (95% confidence level)	215.51	189.13
Upper bound (95% confidence level)	236.11	211.84
Between-Logographeme ISIs (ms)		
Mean	198.41[#]	167.13[#]
Lower bound (95% confidence level)	189.46	154.62
Upper bound (95% confidence level)	207.37	179.64
Within-Logographeme ISIs (ms)		
Mean	144.44[#]	146.50[#]
Lower bound (95% confidence level)	134.55	135.46
Upper bound (95% confidence level)	154.33	157.54

[#] Covariates appearing in the model are evaluated at the following values: ISD = 134.32

Table 6.

Estimated marginal means of within-logographeme-, between-logographems-, and between-radicals ISIs of high- and low-frequency PC.

	High Frequency	Low Frequency
Between-Radicals ISIs (ms)		
Mean	210.06[#]	257.87[#]
Lower bound (95% confidence level)	198.18	245.87
Upper bound (95% confidence level)	221.94	269.86
Between-Logographemes ISIs (ms)		
Mean	167.13[#]	203.18[#]
Lower bound (95% confidence level)	155.49	191.77
Upper bound (95% confidence level)	178.76	214.58
Within-Logographeme ISIs (ms)		
Mean	152.23[#]	146.98[#]
Lower bound (95% confidence level)	140.86	135.35
Upper bound (95% confidence level)	163.60	158.62

[#] Covariates appearing in the model are evaluated at the following values: ISD = 133.84