This is an Accepted Manuscript of an article published by Taylor & Francis in Clinical Linguistics & Phonetics on 02 Apr 2019 (Published online), available at http://www.tandfonline.com/10.1080/02699206.2019.1584723.

Grain Size Units of Chinese Handwriting: Development and Disorder

Dustin Kai-Yan Lau

Department of Chinese and Bilingual Studies, Hong Kong Polytechnic University

Correspondence should be addressed to Dustin Kai-Yan Lau, Department of Chinese and Bilingual Studies, Hong Kong Polytechnic University,

AG522, Core A, The Hong Kong Polytechnic University. Email: dustin.lau@polyu.edu.hk

Preferred running head: Grain Size Units of Chinese Handwriting

Abstract

The current study investigated the grain size of writing units used by children in copying Chinese characters using handwriting measures. In Experiment 1, 31 Grade 1 and 31 Grade 5 children studying in mainstream schools in Hong Kong were invited to copy 36 pseudo-characters on an Android tablet. The pseudo-characters were constructed by combining, in their legal positions, radicals that contain two logographemes. The pseudo-characters contain only high frequency radicals in one condition and only low frequency radicals in the other condition. Linear mixed effect modeling was used to analyze the significance of radical frequency, radical free-standing frequency, and logographeme frequency in predicting the inter-stroke intervals after controlling for inter-stroke distance and gestalt boundaries of radicals and logographemes. The results showed that all three frequency measures significantly predicted Grade 5 children's inter-stroke intervals while only logographeme frequency and radical free-standing frequency significantly predicted Grade 1 children's inter-stroke intervals. This indicated that older children demonstrated the use of both small and large grain size units in writing Chinese characters while younger children showed tendency to use small grain size units with the support of some large grain size units that they know in writing Chinese characters. In Experiment 2, a Grade 3 child with writing difficulties was assessed using the same task. Results showed that he demonstrated the use of only small grain size units in writing. Theoretical and clinical implications were discussed.

Keywords: Chinese, handwriting, writing development

Background

Literacy learning is a complex process that requires the integration of knowledge of the phonological, morphological, and orthographic systems of a language. Comparatively, learning to write words with opaque orthographies, like Chinese, is considered even more difficult, particularly because the relations between phonology and orthography are not consistent. In the last two decades, a sizeable number of studies have been conducted to investigate how children learn to read Chinese (e.g., Ho & Bryant, 1997; Siok & Fletcher, 2001; Tong & McBride-Chang, 2010). Relatively few, however, have been conducted to explore how children learn to write Chinese.

The Chinese writing system is morphosyllabic, 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 rectangular construction. For example, the character "下" corresponds to the syllable /haa6/ and the morpheme [down] and is constructed by positioning the three strokes "一", "丨", and "丶" in a specific pattern. Although characters directly correspond to syllables and morphemes, they are not the only orthographic units in the lexicon. There is a major group of characters in Chinese called phonetic compounds that are composed by combining semantic radicals that give clues to meanings and phonetic radicals that give clues to phonology. For example, the character "橡" /zoeng6/ [oak][1] contains the semantic radical "木" /muk6/ [wood] that gives clues to its meaning and the phonetic radical "象" /zoeng6/ [elephant] that gives clues to its phonology.

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

It has been reported that semantic and phonetic radicals play important roles in reading Chinese characters (e.g., Perfetti & Tan, 1998; Zhou & Marslen-Wilson, 1999).

Previous psycholinguistic studies have demonstrated that phonetic radicals are involved in the recognition of Chinese phonetic compounds (e.g., Hue, 1992; Lau, Leung, Liang, & Lo, 2015; Weekes & Chen, 1999). Particularly, it has been reported that low-frequency regular phonetic compounds, characters that share the same syllables with their corresponding phonetic radicals, have significantly shorter reading latencies than irregular ones. Moreover, the role of phonetic radicals in character processing has also been evidenced in neural responses in event-related potential (ERP) experiments (e.g., Lee, Tsai, Chan, Hsu, Hung, & Tzeng, 2007; Yum, Law, Su, Lau, & Mo, 2014). For example, Yum et al. (2014) reported larger N170, smaller P200, and larger N400 elicited from regular compared with irregular characters using a delayed naming task, confirming that phonetic radicals are involved in the processing of phonetic compounds.

Similarly, previous studies have also documented the role of semantic radicals in the processing of Chinese phonetic compounds (e.g., Feldman & Siok, 1999; Li & Chen, 1999; Zhou & Marslen-Wilson, 1999). In general, it has been reported that low-frequency phonetic compounds with semantically transparent semantic radicals, those that share similar meanings with their corresponding characters, are recognized faster and more accurately than those without semantically transparent semantic radicals. The observations of the use of sub-lexical units in the recognition of Chinese characters have led to speculations of whether similar sub-lexical processing is also involved in Chinese character writing.

In fact, the role of semantic and phonetic radicals in the processing of phonetic compounds has been reported not only in reading but also in writing Chinese characters. One approach to investigating the Chinese writing process involved observing dysgraphic patients who had suffered from strokes and had normal writing abilities before the strokes (e.g., Lau

& Ma, 2018; Law, Yeung, Wong & Chiu, 2005). For example, Law et al. (2005) tested a Chinese dysgraphic patient using writing-to-dictation and written-naming tasks and reported that the patient produced errors that involved substitutions, additions, and deletions of strokes, phonetic radicals, or semantic radicals, indicating that apart from strokes, phonetic and semantic radicals were involved as functional processing units in the writing process. Particularly, Law et al. (2005) observed that the semantic radical substitution errors produced by the patient were semantically related to the targets in the writing-to-dictation task and concluded that the semantic radicals in the mental representations were connected with their corresponding semantic features; hence, they were involved in character writing. In another study using a writing-to-dictation task, Lau and Ma (2018) reported a patient suffering from dysgraphia whose semantic deficits demonstrated more preserved phonetic radicals when the syllable-to-radical mapping was consistent. Similarly, Lau and Ma (2018) concluded that phonetic radicals in mental representations were activated directly by their corresponding syllables and were involved in character writing.

Apart from semantic and phonetic radicals, another type of sub-lexical unit observed in writing Chinese characters has been reported in the literature. In the study conducted by Law and Leung (2000), they reported a Chinese dysgraphic patient who produced writing errors that involved substitutions of logographemes (i.e., stroke patterns in radicals that were spatially separated, such as “幺”,“⺍”, “士”, and “口” in the radicals “糹” and “吉”, respectively, as shown in Figure 1). Similarly, in another study by Han, Zhang, Shu, and Bi (2007), another stroke patient produced similar errors of logographeme substitutions, deletions, and transpositions. All of these authors concluded that besides radicals and strokes, logographemes are also functional processing units in writing Chinese characters. Since all the dysgraphic patients produced writing errors in all units (i.e., strokes, logographemes, and radicals), it has been suggested that orthographic units with different grain sizes are organized in orthographic representations at the same level in the mental lexicon (Law et al., 2005) and are all involved in the writing process. What remains unknown is how Chinese children develop the use of logographemes and radicals as writing units. To investigate this, studying children's writing process is necessary.

By analyzing the stroke sequence errors produced in Chinese children's character writing, Law, Ki, Chung, Ko, and Lam (1998) reported that most Grade 1 children followed the major stroke sequence rule when they wrote; however, without the manipulation of logographeme and radical properties in their stimuli, it was still unclear whether the children used bigger units as logographemes and radicals in their writing. Using a writing-to-dictation task, Meng, Shu, and Zhou (2000) reported higher accuracies associated with regular and semantically transparent characters among Grade 4 children's performances, which indicated that children are sensitive to the functions of semantic and phonetic radicals when they write Chinese characters.

Studies on the role of logographemes in children's character writing are quite rare. Lui (2012) collected the diction workbooks of children from Grade 1 to Grade 6 and analyzed the writing errors produced by the children in different grades. Lui (2012) reported that lower-grade children produced mostly logographeme errors, while children at higher-grade levels produced more radical errors. Lui (2012) proposed that the children progressed from initially using logographemes in writing to later using radicals in writing.

However, several methodological issues have been identified. First, because current research on Chinese writing has relied heavily on the observations of errors produced by individuals to infer the functional writing units used by them, it is not possible to infer the writing units used in their correct writing trials. Second, because children are less prone to making 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 must be used. However, the use of less frequently occurring stimuli not only limits the generalizability of the results but may also yield unwanted results, as substitutions of homophonous characters may occur. This makes the analysis of the written outcome of the target characters impossible. Finally, even if errors are successfully elicited from the participants, it is still unclear whether the elicited writing processes are the result of the use of compensatory strategies in writing solely unfamiliar stimuli. To address these methodological issues, the current study investigated the change of grain size of writing units used by children across grades using handwriting experiments.

To achieve this, both high- and low-frequency radicals that consisted of two logographemes were selected as stimuli in the current study. The radicals were larger grain size units while the logographemes were smaller grain size units. To allow fair comparisons between grade levels, pseudo-characters created by combining either the selected high-frequency or low-frequency radicals in their legal positions were used as stimuli in the experiment. It was expected that if a participant used units of a particular grain size in his/her writing, the familiarity effect of that grain size unit would be observed in his/her writing performance. To capture this familiarity effect, handwriting measures were used.

By comparing the inter-letter intervals (ILIs) between and within sub-lexical units, previous studies have reported that when people write words, they spend more time on the ILI located at syllable and/or morpheme boundaries in words than the ILI not located at the boundaries (e.g., Kandel, Peereman, Grosjacques, & Fayol, 2011; Kandel, Spinelli, Tremblay, Guerassimovitch, & Alevarez, 2012). Using the anticipatory conception of handwriting production (Van Galen, 1991), these studies attributed the longer ILI at the boundaries to the time needed to retrieve successive writing units (i.e., syllables or morphemes). In general, it was reported that children and adults used sub-lexical linguistic-oriented chunks, such as syllables and morphemes (Kandel et al., 2012), as processing units in writing words. In short, handwriting experiments are effective ways of investigating lexical encoding processes, especially functional writing units, used by children in word writing.

To apply similar handwriting experiments to Chinese, each participant in the current study was instructed to write using a wireless pen in the form of a capacitive stylus on the screen of a tablet. The tablet then recorded the durations and positions (coordinates) each time the capacitive stylus touched and left the screen. The inter-stroke intervals (ISIs) were then analyzed to infer the functional writing units that each participant realized. For example, Figure 1 below illustrates the strokes, labeled A to L, for the character 結. A_0 indicates the starting position of stroke A and A_1 indicates its ending position, B_0 indicates the starting position of stroke B and B_1 indicates its ending position, and so on. If a participant used logographemes as writing units, s/he should have performed better in copying familiar logographemes than unfamiliar logographemes, because the stroke sequence in familiar logographemes should already be well-defined in the participant's mental lexicon, namely, that ISIs within logographemes should be shorter, and vice versa. Therefore, if a participant used logographemes as writing units, it was expected that the ISIs within the logographemes would be predicted by the logographeme frequencies, defined as the number of different characters that a logographeme occurred in. Similarly, if a participant used radicals as the writing units, s/he should have performed better in copying familiar radicals than unfamiliar radicals. In the current study, radical familiarity was manipulated by radical frequency, defined as the number of different characters containing the corresponding target radicals and the frequency of occurrence of the target radicals as free-standing characters. Therefore, if a participant used radicals as writing units, it was expected that the ISIs within the radicals would be predicted by radical frequencies and/or the radicals' free-standing frequencies.

Using this method, functional writing units realized by each individual participant in writing Chinese characters could be inferred objectively.

Insert Figure 1 about here

Experiment 1

Method

Participants

Initially, a total of 80 Chinese students were recruited from an ordinary mainstream primary school in Hong Kong. All participants were native Cantonese speakers and had received education in Hong Kong since first-level kindergarten. Six standardized tests were administered, including Raven's Standard Progressive Matrices (Raven, 1986), the Visual Memory Test and the Visual Spatial Test in the Visual-Perceptual Skills (non-motor) Revised (Gardner, 1996), the Test of Visual-Motor Skills (Gardner, 1996), and the Hong Kong Test of Specific Learning Difficulties in Reading and Writing (Ho, Chan, Tsang, & Lee, 2000), to ensure that the participants had normal non-verbal intelligence, visual memory, visual spatial perception, visual motor coordination, and Chinese reading abilities. After the initial assessment, 31 participants from Grade 1 (mean age = 7;08) and 31 participants from Grade 5 (mean age = 11;2) were identified as having fulfilled the following inclusive criteria: scoring at least 85 on Raven's Standard Progressive Matrices (Raven, 1986), above -1 SD on the Visual Memory Test, above -1 SD on the Visual Spatial Test, above -1 SD on the Test of Visual Motor Skills, and above -1 SD on the Hong Kong Test of Specific Learning Difficulties in Reading and Writing (Ho et al., 2000). The demographic data of the identified participants are summarized in Table 1 below:

Insert Table 1 about here

Materials and procedures

A total of 28 low-frequency radicals (e.g., 吉, 肙, etc.) and 30 high-frequency radicals (e.g., 古, 青, etc.) were selected from the Hong Kong Corpus of Primary School Characters (Leung & Lee, 2002). According to Lui, Leung, Law, and Fung (2010), each of the selected radicals contained two logographemes. The logographeme frequencies, radical frequencies, and radical free-standing frequencies of the stimuli are given in Table 2 below. Using the selected list of radicals, a total of 36 pseudo-characters were constructed by combining either two high-frequency or two low-frequency radicals in their legal positions. No selected radicals occurred more than twice in the list of pseudo-characters constructed.

Insert Table 2 about here

Equipment

In the copying task, 7-inch tablets with a resolution of 1820 x 1200 and refresh rate of 60 Hz were used in this study. The tablets were Quad-core with 2.20 GHz processing speed and they ran the latest Android 4.1.1 version. The tablets were installed with a homebrew Android application that controlled the display of stimuli and recorded the written responses of the participants using the open-sourced MotionEvent package.

Tasks

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 trials, a target pseudo-character was displayed and the participants were required to directly write down the presented pseudo-character on the tablet screen using the stylus pen. The participants were instructed to write each stroke precisely and avoid 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 25 minutes.

Measures

The ISI and the inter-stroke-distance (ISD), calculated based on the coordinates where the stylus pen left and retouched the tablet screen between every two successive strokes, were obtained. Moreover, the final written output was also obtained.

Data analysis

Linear mixed-effects models with maximal model structure (Barr, Levy, Scheepers, & Tily, 2013) were computed using the lme4 package (version 1.1-18.1; Bates, Mächler, Bolker, & Walker, 2015) in R (version 3.5.1; R Core Team, 2018) using the ISIs obtained from each of the two grade levels. The radical boundary, the logographeme boundary, and the ISD were entered as covariates. The radical frequency, the radical free-standing frequency, and the logographeme frequency were entered as fixed factors to investigate their significance in predicting the ISIs. By-subject and by-item random intercepts and random slopes were included for each fixed main effect, based on recommendations by Barr et al. (2013). All frequency measures were log-transformed to correct for skewness. Significance was determined using a cut-off point of $t > 2$. The results of the statistical models of the Grade 1 and Grade 5 children are summarized in Table 3 and Table 4 below:

Insert Table 3 about here

Insert Table 4 about here

Results

Data from the items with stroke sequences crossing the logographeme boundaries (a total of 5.5% from Grade 1 and 2.2% from Grade 5) and the ISIs beyond three standard deviations from the mean (a total of 0.7% from Grade 1 and 1.3% from Grade 5) were excluded from the analysis.

The average ISI and ISD located within the logographemes, at the radical boundary and at the logographeme boundary, in the two frequency conditions of the two groups of subjects are summarized in Table 5 below:

Insert Table 5 about here

Grade 1

The results showed that after controlling for the ISD, the ISIs at the radical boundary and at the logographeme boundary were longer than the ISIs within logographemes. Moreover, the ISIs also decreased with the radical free-standing frequency (-7.82 ± 2.61) and decreased with the logographeme frequency (-17.69 ± 4.91). Finally, the prediction of the ISIs by radical frequency was not significant ($p > 0.5$).

Grade 5

The results showed that after controlling for the ISD, the ISIs at the radical boundary and at the logographeme boundary were longer than the ISIs within logographemes. In addition, the ISIs also decreased with radical frequency (-8.04 ± 2.71), decreased with radical free-standing frequency (-2.72 ± 1.08), and decreased with logographeme frequency (-6.53 ± 2.71).

Discussion

The current study aimed at investigating the functional writing units used by Grade 1 and Grade 5 children using handwriting measures. The results obtained from both groups indicated that after controlling for the ISD, the ISIs at the radical and logographeme boundaries were longer than the ISIs within logographemes. There are two possible explanations for the longer boundary-ISIs observed. First, given that the two radicals in each pseudo-character and the two logographemes in each selected radical were spatially separated, the longer boundary-ISIs could be attributed to pauses due to gestalt. Second, the longer boundary-ISIs could also be attributed to the time needed to retrieve and/or for the planning of the successive writing units (e.g., Kandel et al., 2011). To further examine the units used by the two groups, the significance of the radical frequency, radical free-standing frequency, and the logographeme frequency were needed.

Grade 5

The results from the Grade 5 model showed that the ISIs decreased when logographeme frequency increased. This indicated that the Grade 5 children were more efficient in the execution of graphic motor patterns (Ellis & Young, 1988) when copying familiar logographemes. Therefore, the significant logographeme frequency effect confirmed that the Grade 5 children used logographemes as writing units.

Likewise, the observations that the ISIs decreased when radical frequency increased in the Grade 5 model also indicated that the Grade 5 children were more proficient in the execution of graphic motor patterns when copying familiar radicals. Finally, the higher efficiency in executing the graphic motor patterns of familiar radicals was also substantiated by the significant radical free-standing frequency effect observed. This indicated that their use of radicals as writing units was achieved either by recalling the graphic motor patterns of the radicals or the graphic motor patterns of the radicals as free-standing characters.

Grade 1

The results from the Grade 1 model also showed that the ISIs decreased when logographeme frequency increased. Again, this showed that the Grade 1 children used logographemes as writing units. On the other hand, the results showed that the ISIs decreased significantly only when radical free-standing frequency increased, but not when radical frequency increased. This indicated that the Grade 1 children demonstrated mainly the tendency to use radicals as writing units only when they existed as free-standing characters. Hence, the Grade 1 children were less proficient than the Grade 5 children in using radicals as writing units.

Experiment 2

Most of the activities in Hong Kong classrooms involve pencil and paper tasks. The ability to write Chinese characters is essential for daily classroom learning. Individuals suffering from writing difficulties, therefore, suffer greatly in school. Experiment 1 reported the developmental pattern of grain size of writing units used by children across grades. The development from the use of small to large grain size units in writing Chinese characters indicates the need to assess the grain size of writing units used by poor writers. Given the close-to-errorless responses of the children in the direct copying task observed in Experiment 1, the task was very useful for this purpose. Previous studies in Chinese have reported poor orthographic awareness, indicating the poor knowledge of functions and locations of radicals in Chinese characters, observed among poor readers (e.g. Ho, Chan, Chung, Lee & Tsang, 2007). Therefore, it is also possible that poor writers will have difficulties using large grain size units in writing as well.

In this experiment, a developmental poor writer studying in a mainstream primary school in Hong Kong was assessed using the pseudo-character copying task used in

Experiment 1. The results would shed light on the grain size of writing units used by developmental poor writers in Chinese.

Participants

TYP, a 9;01 boy studying in Grade 3 in a mainstream primary school in Hong Kong, was recruited. His literacy and cognitive abilities were assessed using the Raven's Standard Progressive Matrices (Raven, 1986), the Visual Memory Test and the Visual Spatial Test in the Visual-Perceptual Skills (non-motor) Revised (Gardner, 1996), the Test of Visual-Motor Skills (Gardner, 1996), and the Hong Kong Test of Specific Learning Difficulties in Reading and Writing (Ho, Chan, Tsang, & Lee, 2000), and the writing-to-dictation task by Leung & Lui (2005). The results of these initial assessment are summarized in Table 6 below:

Insert Table 6 about here

Method

The same pseudo-character direct copying task used in Experiment 1 was administered.

Results

The average ISI and ISD located within the logographemes, at the radical boundary and at the logographeme boundary, in the two frequency conditions, as well as the results of the statistical models are summarized in Table 7 and Table 8.

Insert Table 7 about here

Insert Table 8 about here

The results showed that after controlling for the ISD, the ISIs at the radical boundary and at the logographeme boundary were longer than the ISIs within logographemes. Moreover, the ISIs also decreased with the logographeme frequency (-14.96 ± 7.47). Finally, the prediction of the ISIs by radical frequency and radical free-standing frequency were not significant ($p > 0.5$).

Discussion

The significant effect of logographeme frequency but insignificant effect of radical frequency and radical free-standing frequency obtained in TYP's writing data indicated clearly that TYP demonstrated the use of small but not large grain size units in his writing. Referring to the results obtained from Experiment 1 that the first graders use small grain size units while the fifth graders use both small and large grain size units in their writing, TYP's performance is considered similar to that of the first graders but different from the fifth graders. Given the absence of a third graders control group in Experiment 1, it may be difficult to confirm if there exists a discrepancy between TYP's performance and the chronological-age-matched controls. Nevertheless, as discussed in Experiment 1, the significant radical free-standing frequency effect observed among the first graders indicated their tendency to use bigger grain size units in their writing when the bigger grain size units existed as free-standing characters. Such tendency, however, was not observed in TYP's performance as the radical free-standing frequency effect was not significant. That TYP uses only small grain size units without the tendency to use bigger grain size units in his writing may indicate a discrepancy from the typically developing children.

The absence of the use of large grain size units in copying Chinese characters by TYP is considered to be related to TYP's writing difficulties. Given that there exists more consistent mappings among orthography, phonology and meaning in large grain size units (phonetic radicals map on syllables, and semantic radicals map on semantic features) than small grain size units. The sole use of small grain size units in TYP's writing suggested the absence of integrations of the systems of orthography, phonology and semantics, hence indicated a poor lexical quality (Perfetti & Hart, 2002). Nevertheless, the nature of the relationship between the writing difficulties and the difficulties of developing the use of larger grain size writing units is unclear. Future work is recommended to investigate whether there exist causal relationship and/or reciprocal relationship between the two.

Clinically, this observation implied the needs to investigate the grain size of writing units used by individuals suffering from writing difficulties. Once the grain size of the writing units predominantly used by an individual suffering from writing difficulties is identified, instructions can be designed accordingly. Specifically, if an individual uses only small grain size units in a copying task, there is a need to introduce larger grain size units to allow the individual to achieve better mappings between phonetic radicals and their corresponding syllables, and between semantic radicals and their corresponding semantic features. Given that the Grade 1 children in the current study demonstrated the use of free-standing radicals before the use of high-frequency bound radicals, this may be a steppingstone for children to learn how to use radicals in their writing. Introducing the use of free-standing radicals as writing units may help to promote the awareness of poor writers in the application of radicals as writing units. Future studies that explore the grain size of writing units used by individuals suffering from writing difficulties in Chinese will warrant this.

General Discussion

Development of grain size of writing units across grades

The results of the current study showed a developmental pattern in the children's storage of graphic motor patterns of writing units of different grain size. While the Grade 1 children relied heavily on the graphic motor patterns of small units, like logographemes, with the support of some larger units (i.e., free-standing radicals) in their writing, the Grade 5 children were more proficient in using the graphic motor patterns of both small and large units in their writing. Such a pattern of development is consistent with the results of a previous study by Lui (2012), while the development from small to large grain size units in the learning of orthographic units is consistent with the suggestions by Ziegler and Goswami (2005).

According to Leung & Lee (2002), over 3,000 traditional characters, with a corresponding number of strokes ranging from 1 to 35, are introduced in primary school. One important goal for primary school children in learning to write Chinese characters is to group frequently occurring stroke clusters into psychological entities for easier retrieval. There are two advantages to grouping stroke clusters in small units compared with grouping them in large units. First, small units consist of fewer strokes; hence, the graphic motor patterns of small units are less complex. Moreover, one has to learn more units if stroke clusters are grouped into large units instead of small units. According to Lui (2012), there are less than 300 logographemes that occur in Chinese characters introduced in primary schools. On the other hand, according to Leung and Lee (2002), there are over 1,000 radicals introduced in primary school. Given these two advantages, it is easier for lower-grade children to group stroke clusters into small units. Nevertheless, logographemes do not usually contribute to meanings nor sounds to characters. To achieve better lexical quality (Perfetti & Hart, 2002), more consolidated mappings between orthographic units and phonological units, as well as between orthographic units and semantic features, are needed as children grow up. Hence, there is a need for older children to learn how to use radicals as writing units upon more exposure. This explains why the mature writers demonstrated radical frequency effects in their writing.

One interesting observation in the current study was the significant radical free-standing frequency effect and insignificant radical frequency effect observed in the Grade 1 participants. The gradual change from using high-frequency free-standing radicals to using both high-frequency free-standing and high-frequency bound radicals in writing is consistent with the Overlapping Waves Model (Siegler, 1996). The Overlapping Waves Model postulates that when children are presented with problems, they will choose from a variety of coexisting repertoires of strategies to solve the problems, depending on the nature of the problem. The model also found that children tend to replace simple strategies with more advanced strategies developmentally. Previous studies have also documented supportive evidence of the Overlapping Waved Model in explaining children's spelling development by reporting that when children learned to spell new words, they used knowledge of phonology, orthography, and morphology even at an early age, and they demonstrated a reliance on different strategies at different time points (e.g., Critten, Sheriston, & Mann, 2016; Kwong & Varnhagen, 2005). The results of the current study indicated that although the children at an early age were mostly familiar with the use of smaller grain size units in their writing, they still managed to use familiar free-standing radicals as writing units in response to the requirements of copying unknown pseudo-characters. When they got older, they were capable of applying different strategies by using logographemes, bound, and free-standing radicals in copying unknown characters. Hence, the current study echoed previous reports and added support to the application of the Overlapping Waves Model in explaining children's writing development in Chinese.

Limitations and future studies

In the current study, since radical stimuli were selected for the investigation of the participants' use of large grain size units, the target radicals all consisted of two logographemes. Therefore, no extremely high-frequency semantic radicals, such as 氵, 亻,

and 扌, were selected. Given that our results support the Overlapping Waves Model, it has been predicted that even Grade 1 children will manipulate extremely high-frequency semantic radicals as writing units. For the insignificant radical frequencies observed in Grade 1 in the current study, instead of indicating that the Grade 1 children did not demonstrate a knowledge of radicals, it only indicated that the Grade 1 children showed a greater tendency to use small than large grain size units in writing Chinese characters. Similar studies that include high-frequency semantic radicals will be needed in the future to support this prediction.

In addition, since the pseudo-characters created in the current study did not correspond to any meanings nor sounds, their constituent radicals served neither as phonetic nor semantic radicals. Therefore, it was not possible to investigate whether the phonological and semantic information associated with phonetic and semantic radicals in typical Chinese phonetic compounds was involved in the copying process. Future studies that use real characters are recommended to answer this question.

Conclusion

The current study investigated the grain size of writing units used by Grade 1 and Grade 5 children in copying Chinese characters using handwriting measures. The results showed that whereas the Grade 5 children demonstrated the use of both small and large grain size units in writing Chinese characters, the Grade 1 children showed a tendency to use small grain size units with the support of some large grain size units in writing Chinese characters. The results support the application of the Overlapping Waves Model in explaining children's writing development.

Disclosure statement

This study was supported by the Departmental General Research Funds from the Hong Kong Polytechnic University. We are grateful to all the children participated in the study.

References

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*, 255–278.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. doi:10.18637/jss.v067.i01.

Critten, S., Sheriston, L., & Mann, F. (2016). Young children's spelling representations and spelling strategies. *Learning and Instruction, 46*, 34–44.

Ellis, A. W., & Young, A. W. (1988). *Human cognitive neuropsychology: A textbook with readings.* Psychology Press.

Feldman, L. B., & Siok, W. W. (1999). Semantic radicals contribute to the visual identification of Chinese characters. *Journal of Memory and Language*, *40*(4), 559–576.

Gardner, M. F. (1996). *Test of visual-perceptual skills (non-motor)*. Burlingame, CA: Psychological and Educational Publications.

Han, Z., Zhang, Y., Shu, H., & Bi, Y. (2007). The orthographic buffer in writing Chinese characters: Evidence from a dysgraphic patient. *Cognitive Neuropsychology, 24*(4), 431–450.

Ho, C. S., & Bryant, P. (1997). Phonological skills are important in learning to read Chinese. *Developmental Psychology,* 33, 946–951.

Ho, C.S.H., Chan, D.W.-O., Chung, K.K.H., Lee, S.-H., & Tsang, S.M. (2007). In search of subtypes of Chinese developmental dyslexia. *Journal of Experimental Child Psychology, 97,* 61-83.

Ho, C. S.-H., Chan, D. W.-O., Tsang, S.-M., & Lee, S.-H. (2000). The Hong Kong test of specific learning difficulties in reading and writing. Hong Kong: Hong Kong Specific Learning Difficulties Research Team.

Hoosain, R. (1992). Psychological reality of the word in Chinese. In H.-C. Chen & O. J. L. Tzeng (Eds.), *Language processing in Chinese* (pp. 111–130). Amsterdam: North-Holland.

Hue, C. W. (1992). Recognition processes in character naming. In H.-C. Chen & O. J. L. Tzeng (Eds.), *Language processing in Chinese* (pp. 93–107). Amsterdam: North-Holland.

Kandel, S., Peereman, R., Grosjacques, G., & Fayol, M. (2011). For a psycholinguistic model of handwriting production: Testing the syllable-bigram controversy. *Journal of Experimental Psychology: Human Perception and Performance, 37*(4), 1310–1322.

Kandel, S., Spinelli, E., Tremblay, A., Guerassimovitch, H., & Alvarez, C. J. (2012). Processing prefixes and suffixes in handwriting production. *Acta Psychologica, 140*, 187–195.

Kwong, T. E., & Varnhagen, C. K. (2005). Strategy development and learning to spell new words: Generalization of a process. *Developmental Psychology, 41*(1), 148–159.

Lau, D. K.-Y., Leung, M. T., Liang, Y., & Lo, C. M. J. (2015). Predicting the naming of regular-, irregular- and non-phonetic compounds in Chinese. *Clinical Linguistics & Phonetics, 29*(8-10), 776–792.

Lau, D. K. Y., & Ma, K. H. W. (2018). A phonetic radical account of the phonology-to-orthography consistency effect on writing Chinese characters: Evidence from a Chinese dysgraphic patient. *Cognitive Neuropsychology, 35*(8), 403–414. doi:

10.1080/02643294.2018.1510387.

Law, N., Ki, W. W, Chung, A. L. S., Ko, P. Y., & Lam, H. C. (1998). Children's stroke sequence errors in writing Chinese characters. In C. K. Leong & K. Tamaoka (Eds.), *Cognitive processing of the Chinese and the Japanese languages* (pp. 113–138). Netherlands: Kluwer Academic Publishers.

Law, S. P., & Leung, M. T. (2000). Structural representations of characters in Chinese writing: Evidence from a case of acquired dysgraphia. *Psychologia, 43*, 67–83.

Law, S. P., Yeung, O., Wong, W., & Chiu, K. M. (2005). Processing of semantic radicals in writing Chinese characters: Data from a Chinese dysgraphic patient. *Cognitive Neuropsychology, 22*(7), 0885–0903.

Lee, C. Y., Tsai, J. L., Chan, W. H., Hsu, C. H., Hung, D. L., & Tzeng, O. J. L. (2007). Temporal dynamics of the consistency effect in reading Chinese: An event-related potentials study. *NeuroReport, 18*, 47–151. doi:10.1097/WNR.0b013e328010d4e4.

Leung, M. T. & Lee, A. (2002). The Hong Kong corpus of primary school Chinese. Paper presented at the *Ninth Meeting of the International Clinical Phonetics and Linguistic Association*.

Li, H., & Chen, C.-H. (1999). Radical processing in Chinese character recognition: Evidence from lexical decision. *Psychologia, 42*, 199–208.

Lui, H.-M. (2012). The processing units of writing Chinese characters: A developmental perspective. Unpublished M.Phil. thesis. The University of Hong Kong.

Lui, H.-M., Leung, M.-T., Law, S.-P., & Fung, R. S.-Y. (2010). A database for investigating the logographeme as a basic unit of writing Chinese. *International Journal of Speech-Language Pathology, 12*(1), 8–18.

Meng, X., Shu, H., & Zhou, X. (2000). Children's Chinese character structure awareness in character output. *Psychological Science, 23*, 260–264.

Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. In L. T. Verhoeven, C. Elbro, & P. Reitsma (Eds.), *Precursors of functional literacy* (pp. 189 –214). Amsterdam: John Benjamins.

Perfetti, C. A., & Tan, L. H. (1998). The time course of graphic, phonological, and semantic activation in Chinese character identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*(1), 101.

Raven, J. C. (1986). *Hong Kong supplement to guide to the standard progressive matrices.* Hong Kong: HKSAR Government, Education Department.

Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking.* New York: Oxford University Press.

Siok, W. T., & Fletcher, P. (2001). The role of phonological awareness and visualorthographic skills in Chinese reading acquisition. *Developmental Psychology, 37*, 886–899.

Tong, X., & McBride-Chang, C. (2010). Longitudinal predictors of very early Chinese literacy acquisition. *Journal of Research in Reading, 33*, 1–18.

Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10*, 165–191.

Weekes, B., & Chen, H.-Q. (1999). Surface dyslexia in Chinese. *Neurocase, 5*, 101–112.

Yum, Y. N., Law, S.-P., Su, I.-F., Lau, D. K.-Y., & Mo, K. N. (2014). An ERP study of effects of regularity and consistency in delayed naming and lexicality judgment in a logographic writing system. *Frontiers in Psychology, 5*, 315.

Zhou, X., & Marslen-Wilson, W. (1999). Sublexical processing in reading Chinese. In J. Wang, A. Inhoff, & H.-C. Chen (Eds.), *Reading Chinese script: A cognitive analysis* (pp. 37–63). Hillsdale, NJ: Lawrence Erlbaum Associates Inc.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*(1), 3–29.

Figure 1. Examples of radicals, logographemes, stroke organization and ISI and ISD calculations.

Table 1. Participants' age, gender, and scores on the Raven, reading, and visual tests

	Grade 1 **Mean (SD)**	**Grade 5** **Mean (SD)**
N	31 (17 female)	31 (18 female)
Age	7.11 yrs. (0.28)	11.2 yrs. (0.44)
Raven		
Raw score	33.9 (9.1)	44.2 (7.5)
Standard score	115.7 (14.1)	102.0 (16.2)
Word reading subtest of SpLD		
Raw score	79.2 (24.3)	138.1 (7.2)
Standard score	0.96 (1.03)	0.4 (0.6)
Gardner – Visual Memory (percentile score)	110.0 (11.4)	105.0 (6.4)
Gardner – Visual Spatial (percentile score)	123.0 (7.5)	114.3 (5.4)
Gardner – Visual Motor (percentile score)	109.3 (10.1)	102.6 (6.5)

Table 2. Means and standard deviations of number of strokes, radical frequency, radical free-standing frequency, and logographeme frequency of the two categories of radicals selected

	High-frequency Radicals	**Low-frequency Radicals**	
N	30	28	
Number of strokes			
Mean (SD)	5.81 (1.58)	6.19 (1.43)	
Radical frequency^			
Mean (SD) at Grade 1	5.31 (5.64)	1.00 (0.00)	***
Mean (SD) at Grade 5	13.61 (17.89)	1.22 (0.87)	***
Radical free-standing frequency			
Mean (SD) at Grade 1	25.97 (39.94)	1.44 (7.21)	***
Mean (SD) at Grade 5	308.64 (433.86)	12.67 (35.03)	***
Logographeme frequency			
Mean (SD) at Grade 1	76.31 (103.16)	67.58 (101.82)	
Mean (SD) at Grade 5	207.13 (269.54)	186.57 (265.76)	

^ All frequency values obtained from the Hong Kong Corpus of Primary School Characters (Leung & Lee, 2002).

*** $p < .0001$

Table 3. Results of the model examining the predictors of the ISIs obtained in Grade 1

Fixed Effects	**Estimate**	**SE**	**t**
(Intercept)	662.75	0.119	21.70
ISD	0.90	0.011	16.01
Radical boundary	238.56	0.015	34.58
Logographeme boundary	148.96	0.028	34.03
Radical frequency	-6.06	9.98	-1.21
Radical free-standing frequency	-7.82	2.61	-3.00
Logographeme frequency	-17.69	4.91	-3.61

Random Effects	**Variance**	**SD**	**Correlation**	
Intercept|Subject	20.227	0.450		
Radical free-standing frequency|Subject	0.034	0.018	-1.00	
Logographeme frequency|Subject	0.183	0.043	-1.00	-1.00
Intercept|Item	7.557	0.275		
Radical free-standing frequency|Item	0.012	0.011	0.21	
Logographeme frequency|Item	0.090	0.030	-0.93	-0.55

Table 4. Results of the model examining the predictors of the ISIs obtained in Grade 5

Fixed Effects	**Estimate**	**SE**	**t**
(Intercept)	350.65	20.72	16.92
ISD	0.58	0.03	21.04
Radical boundary	110.82	3.68	30.14
Logographeme boundary	53.00	2.39	22.20
Radical frequency	-8.04	2.71	-2.96
Radical free-standing frequency	-2.72	1.08	-2.52
Logographeme frequency	-6.53	2.71	-2.41

Random Effects	**Variance**	**SD**	**Correlation**		
Intercept|Subject	9086.87	95.33			
Radical frequency|Subject	62.34	7.90	-0.73		
Radical free-standing frequency|Subject	4.37	2.09	-0.48	0.08	
Logographeme frequency|Subject	7.74	2.78	-0.80	0.18	0.63
Intercept|Item	19651.11	140.18			
Radical frequency|Item	14.84	3.85	-0.19		
Radical free-standing frequency|Item	2.44	1.56	0.93	-0.54	
Logographeme frequency|Item	774.31	27.83	-0.96	-0.11	-0.78

Table 5. Means and standard deviations of the ISIs and the ISD at radical boundary, logographeme boundary, and within logographeme in the two frequency conditions

	High-frequency Condition	Low-frequency Condition
Grade 1		
Radical boundary		
Mean ISI (in ms)	871.55 (514.49)	854.12 (500.34)
Mean ISD	212.87 (79.89)	211.14 (82.07)
Logographeme boundary		
Mean ISI (in ms)	495.60 (438.15)	640.10 (464.43)
Mean ISD	106.72 (58.24)	118.66 (58.08)
Within logographeme		
Mean ISI (in ms)	293.14 (244.08)	283.70 (224.36)
Mean ISD	91.92 (48.67)	86.58 (47.91)
Grade 5		
Radical boundary		
Mean ISI (in ms)	447.47 (275.48)	481.82 (281.29)
Mean ISD	219.00 (85.14)	224.15 (85.44)
Logographeme boundary		
Mean ISI (in ms)	260.86 (169.98)	327.94 (231.43)
Mean ISD	110.52 (56.20)	125.08 (55.36)
Within logographeme		
Mean ISI (in ms)	194.77 (117.76)	198.20 (118.80)
Mean ISD	100.67 (48.95)	94.97 (47.95)

Table 6. TYP's scores on the Raven, reading, writing, and visual tests

	Mean (SD)
Age	9.08 yrs.
Raven	
Raw score	34
Standard score	95.0
Word reading subtest of SpLD	
Raw score	103
Standard score	-0.33
Gardner – Visual Memory (percentile score)	70.0
Gardner – Visual Spatial (percentile score)	92.0
Gardner – Visual Motor (percentile score)	95.0
Writing-to-dictation	
Raw score	8 out of 30
Standard score	-1.58

Table 7. Means and standard deviations of the ISIs and the ISD at radical boundary, logographeme boundary, and within logographeme in the two frequency conditions from TYP's writing

	High-frequency Condition	**Low-frequency Condition**
Radical boundary		
Mean ISI (in ms)	434.24 (238.13)	475.33 (247.87)
Mean ISD	172.71 (59.12)	163.58 (53.01)
Logographeme boundary		
Mean ISI (in ms)	256.00 (140.65)	333.97 (227.74)
Mean ISD	84.08 (35.97)	97.24 (37.17)
Within logographeme		
Mean ISI (in ms)	219.02 (132.92)	212.87 (101.39)
Mean ISD	75.60 (32.49)	69.97 (33.19)

Table 8. Results of the model examining the predictors of the ISIs obtained in TYP's writing

Fixed Effects	**Estimate**	**SE**	**t**
(Intercept)	351.45	51.68	6.80
ISD	0.83	0.19	4.31
Radical boundary	78.05	14.60	5.35
Logographeme boundary	34.12	8.80	3.88
Radical frequency	-8.45	11.56	-0.73
Radical free-standing frequency	-1.95	7.47	-0.52
Logographeme frequency	-14.97	7.47	-2.01