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Chinese spelling – evidence from pen tablets

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Abstract

Studies that investigated how people decode words from the phonological input (listening) and orthographic input (reading), as well as the encoding of words for phonological output (speaking) and orthographic output (spelling / writing) allow researchers to understand the structure of the lexicon and how lexical representations interact. In this chapter, findings from previous studies investigating the Chinese character writing based primarily on error analyses and the corresponding limitations were first reviewed. Next, new findings obtained from studies investigating Chinese character writing using pen and digital tablets and their theoretical implications were summarized. Finally, future research directions in this topic were suggested.

Introduction

Words are symbols or codes representing meanings used by people to communicate with others every day. For decades, researchers tried to unveil the structure of the lexicon, the collection of words, and how lexical representations interact. Words can be expressed in phonological (spoken) or orthographic (written) forms to convey messages. Similarly, words expressed in phonological or orthographic forms are picked up to decipher messages conveyed by others. Therefore, studies of lexical processing usually focus on how people achieve the decoding of phonological input and orthographic input, as well as the encoding of phonological output and orthographic output.

In alphabetic languages, the orthographic units can be represented as written alphabets (e.g. “a”, “c”), or spoken names of the alphabets (e.g. “ay”, “si”). Therefore, the encoding process of orthographic output can be studied using spelling, typing, or writing. On the other hand, in non-alphabetic languages, like Chinese, the orthographic units do not always have names. Therefore, studying the encoding process of orthographic output in Chinese is usually conducted using writing.

The architecture of the writing process can be categorized into the central and peripheral processing (Ellis & Young, 1996; Bonin et al., 2015). The processing involving the orthographic long-term memory, conversion from phonology to orthography, and orthographic short-term memory are usually categorized as the central processing. Orthographic codes retrieved from the central processing are then externalized via the peripheral processing, which includes allograph selection, graphic motor pattern selection, and graphic motor pattern execution.

No matter alphabetic or non-alphabetic languages are studied, they share the common research foci of the encoding process of orthographic output, including (1) the grain size of the processing units (Ziegler & Goswami, 2005), which indicate the forms of orthographic units represented in the lexicon, and (2) the phonological, orthographic and semantic effects in the process, which indicate how the lexical representations interact during the encoding process, and (3) how the peripheral processing interacts with the central processing in the writing process.

In this chapter, findings from investigations of the central and peripheral processing of Chinese character writing were reviewed. Their corresponding theoretical implications were summarized in the format of a processing model. Finally, future research directions in this topic were discussed.

Characteristics of Chinese

In general, Chinese is morphosyllabic, in that each Chinese character corresponds to one syllable and one morpheme (Hoosain, 1992). For example, the character “大” corresponds to the syllable [daai6][1] and the meaning <big>. The example “大” in the above

[1] Examples in this paper are given using traditional Chinese characters and Cantonese. Phonetic transcriptions are represented in jyutping, a romanization system developed by the Linguistic Society of Hong Kong.

is constructed by organizing the three strokes “ 一”, “ 丿”, and “ ㇏” in a specific pattern within a rectangular construction. There is a major group of Chinese characters called phonetic compounds that contain radicals that give clues to phonology and meaning. For example, the character 獅 [si1] <lion> contains the semantic radical 犭 <animal-related>, which gives clues to its meaning, and the phonetic radical 師 [si1], which gives clues to its phonology. The clues to meaning and phonology are not always transparent. For example, although the character 犯 [faan6] <criminal> shares the same sematic radical 犭, the overlapping in terms of meanings between the two is considered minimal. The measure of the overlapping in terms of meanings between characters and the corresponding semantic radicals is referred to as semantic radical transparency. In the above, 獅 is considered having high semantic radical transparency while 犯 is considered having low semantic radical transparency. Similarly, the clues to phonology by phonetic radicals are not always transparent. For example, although the character 篩 [sai1] <filter> shares the same phonetic radical 師 [si1], the two syllables are not identical. Characters that share the same syllables with their corresponding phonetic radicals are called regular characters while those that do no are called irregular characters.

Investigating Chinese spelling: error analyses

Before the common availability of pen and digital tablets, most of the previous studies that have investigated the Chinese writing process relied on the observation of errors produced by patients with acquired dysgraphia who had normal writing abilities before suffering from brain injuries (E.g. Law, 2004; Law & Or, 2001). These case studies were mostly conducted using the cognitive neuropsychological approach. Using this approach, theorists inferred the functional structure of the normal cognitive system according to the errors produced by the patients studied. The inference were based on the universality assumption, that the functional structure of cognitive systems is universal across all individuals, and the subtraction assumption, that the errors produced by brain-injured patients are due to the subtractions of the impaired functions from the normal system, instead of new functions added (Basso, 2003).

Law et al. (2005) observed a Chinese patient with dysgraphia using writing-to-dictation and written-naming tasks. They reported that the patient produced errors that involved substitutions, additions, and deletions of strokes, phonetic radicals, or semantic radicals. It was hypothesized that the errors indicated that strokes and radicals are writing units used in Chinese character writing. In another study, Law and Leung (2000) reported a Chinese patient with dysgraphia who produced writing errors that involved the substitution of logographemes (stroke clusters in radicals that frequently occur in other characters, e.g., 厶 and 口 in the radical 台). Similar errors of logographeme substitutions, deletions, and transpositions were observed in the writing of another patient studied by Han et al. (2007). They hypothesized that apart from strokes and radicals, logographemes are also writing units used in Chinese character writing. Based on these case reports, it was suggested that orthographic units with different grain sizes are represented in the orthographic domain in the mental lexicon (Law et al., 2005).

In addition, since the non-character responses with semantic radical substitutions or insertion produced by the patient described in Law et al. (2005) were semantically related to the meaning of the target characters, it was further hypothesized that semantic features are directly connected with semantic radicals in the orthographic domain, such that direct activation of semantic radicals from the semantic features is possible. Similarly, by analyzing the phonological relations of the errors associated with phonetic radicals produced by the dysgraphic patient, Lau & Ma (2018) suggested that direct activation of phonetic radicals from the phonological domain is possible.

Although these case studies served well the purpose of investigating the functional structure of the cognitive processes of Chinese character writing, there are several limitations of studying this topic by relying solely on errors made by patients with dysgraphia.

First, due to the lateralization of the brain function, individuals suffering from acquired dysgraphia usually have left-brain injury, which will result in contralateral paralysis of the right limbs. In other words, the patients, among which most are right-handed premorbid, may have to use their left hand to perform in the writing tasks. To what extent their written output may be affected by the use of their non-dominant left hand in writing is unknown. In fact, many patients refused to use their left hand to write or simply easily give up in the clinical settings.

Another limitation is that patients with “pure” impairments are not always available. To infer from errors produced by patients, individuals suffering from severe brain injury that affected a large extent of the cognitive functions are usually not preferred, either because the errors produced were not informative enough (e.g. lots of no response trials observed), or that there are too many disruptions in the individual’s cognitive functions, hence too many possibilities to explain the errors, which makes the investigation inconclusive. Waiting for the “ideal” patients to show up in clinics is considered too inefficient and impractical.

Next, even if the “ideal” patient does show up in the clinic, inferring from errors produced may induce the problem of stimuli bias. For example, patients usually demonstrate more errors when they were presented with low frequency instead of high frequency items. In such a case, the investigation of the processing of high frequency items may not be easily achieved. Finally, while it is possible to limit the potential source of errors by hypothesizing certain disruptions in the normal system to explain the errors produced, it is not as possible to hypothesize why the accurate trials were correctly produced. For the latter, there are simply too many possibilities.

To address these limitations, researchers started to wonder how they can make good use of pen and digital tablets to study the writing process.

Investigating Chinese spelling – measures of response time

The availability of digital tablets makes latency measures available. One of the most common latency measure in handwriting task is the response time (RT) of accurate trials, usually measured as the time difference between the onset of a stimuli (either auditory or visual) and the first touch of the stylus on the tablet surface.

Representations in the orthographic domain

For example, using a word learning task associated with an implicit priming paradigm, Chen & Cherng (2013) compared the significance of logographemes and radicals with reference to strokes in the writing process. They instructed their participants to first learn lists of two-character words. Later in the recall phase, the participants were required to write down the second characters of the learnt words upon the presentation of the first characters as prompts. In the recall phase, the items were sorted either in random order (referred as the heterogenous condition) or according to shared initial strokes, initial logographemes or initial radicals (referred as the homogeneous condition). Shorter RTs, when compared with the heterogeneous condition, were observed in the homogeneous conditions only if the targets shared initial logographemes or initial radicals, but not if the targets shared initial strokes. The results were taken as evidence to support that logographemes and radicals are represented in the orthographic domain for writing production of Chinese characters.

However, using a similar experimental design, Damian and Qu (2019) reported that shorter RTs were observed among shared initial radical items but not among the shared initial logographeme items, when compared with the heterogeneous condition. Obviously, the result raised some doubts regarding the notion that logographemes play a role in Chinese character writing. Nevertheless, Damian and Qu (2019) also speculated that the different results as compared with Chen and Cherng (2013) may be attributed to the fact the Damian and Qu (2019)'s experiment was conducted in simplified Chinese while Chen and Cherng (2013)'s experiment was conducted in traditional Chinese. However, the exact reason for the discrepancy in findings remains unclear.

Role of phonology in spelling Chinese

Latency measures were also applied in studies that investigate the role of phonology in writing Chinese characters. Qu et al. (2011) used a picture written-naming task in which pictures are presented with distractor words to test the phonological contribution in Chinese character writing. They manipulated the distractor types by comparing unrelated distractors with either distractors that are both phonologically and orthographically overlap with the targets or distractors that are only phonologically overlap with the targets. They reported that shorter naming RTs associated with both types of "related" distractors compared with unrelated distractors when the distractors were presented simultaneously with the pictures. In addition, they also observed that if the distractors were presented with a time lag of 100ms, shorter naming RTs only associated with phonological-orthographic-related distractors when compared with unrelated distractors. This was taken as evidence to support the idea of early activation of phonological information of target words in the written naming process.

In another study by Qu et al. (2016), the picture written-naming task was used with the masked priming paradigm, in which the pictures were preceded by brief and masked presentation of the distractors. Similar findings were reported, which further support the idea that phonological information is involved in written word production.

Turning phonological code into orthographic code

Another commonly asked question in studying Chinese character writing using latency measures concerns how individuals turn phonological codes into orthographic codes. Using writing-to-dictation tasks, in which auditory stimuli were presented and participants were instructed to write the characters representing the presented syllables, Han et al. (2012) observed that RTs were modulated by both homophone density, measured as the number of homophones sharing the same syllable, as well as other semantic-related variables such as imageability and concreteness. The results were taken as evidence to support the dual route account of Chinese writing-to-dictation suggested by Weekes et al. (2006). According to this dual route account, the process of turning phonological codes into orthographic codes can be achieved in the direct lexical pathway and the lexical-semantic pathway. One issue about Han et al. (2012)'s study was that a single syllable was presented each time and the participants were instructed to respond by writing whichever characters they can first think of associated with the target syllable. Given the homophonous nature of Chinese, the significance of homophone density in their results may be prompted by the task requirement instead. To address this, Lau (2021) modified the writing-to-dictation task by giving word contexts of the targets so as to specify the target morphemes (e.g. "「背包」嘅「背」字" [the 'back' in 'backpack']). It is interesting that after specifying the target morphemes, the accuracy was not affected by homophone density while RT was still modulated by homophone density. Lau (2021) suggested that the insignificant effect of homophone density in predicting accuracy of writing-to-dictation was attributed to the homophonous nature of the Chinese writing system that discourages users from relying heavily on the phonology-to-orthography conversion approach in writing. Consequently, confusions in communication due to lots of errors of homophone substitutions in daily writing can be avoided. Nevertheless, as RT was modulated by homophone density, it was also suggested that a single lexical-semantic route is not sufficient to explain writing-to-dictation in Chinese. Hence, the dual route account is, again, supported with evidence.

Recent studies of writing-to-dictation of Chinese also investigated the role of phonetic and semantic radicals in the process. Using large-scale experiment that involves over 3000 characters, Wang et al. (2020) observed that shorter dictation RTs were associated with phonetically regular characters. In another large-scale study, Yum et al. (2022) also observed shorter dictation RTs among characters with high semantic radical transparency. The importance of these two studies is that they do not only added the role of sublexical units (i.e., phonetic and semantic radicals) in the writing process, they also provided support to the notion that semantic and phonetic radicals are represented in the orthographic domain ready for direct activations from the semantic and phonological domains (Lau & Ma, 2018; Law et al., 2005).

Investigating Chinese spelling – measures of writing fluency beyond RT

Unlike other psycholinguistic experiments in which the processing is assumed to be completed once the participants made responses, such as word/picture naming and lexical decision which require the participants to produce item names or press certain buttons as responses correspondingly, experiments requiring handwriting responses offer the window for researchers to observe the cognitive process beyond the time at which the first attempts of responses was made. In fact, there is a growing body of evidence suggesting that certain cognitive processes involved in the encoding process, instead of completed right at the beginning of the writing process, also occur during writing (Delattre et al., 2006; Qu et al., 2011). Therefore, applying measures of writing fluency beyond RT (Parret & Olive, 2019) to inform about the writing process has become more popular.

For example, Kandel et al. (2006) instructed their participants to copy suffixed and pseudo-suffixed words and measured the inter-letter time intervals in the handwriting production of their participants. It was observed that significantly longer inter-letter time intervals at the morpheme-boundary among suffixed but not pseudo-suffixed words. The longer inter-letter time intervals were attributed to the extra processing time for the anticipation of the production of suffixes. Such result is consistent with the predictions of the notion of decomposed processing of morphologically complex words (Kuo & Anderson, 2006; Lau et al., 2017; Liu & McBride, 2010). The observation of this effect of morphological decomposition during the handwriting production further supports the notion of central processing cascading over peripheral processing during handwriting.

Representations in the orthographic domain

Using an immediate copying task with over 200 items, Lau (2020b) obtained the handwriting data of 100 participants. Specifically, the inter-stroke intervals (ISI) located at radical boundaries, ISI located at logographeme boundaries and ISI within logo graphemes were compared. Examples of unit boundaries are given in Figure 1. It was reported that after controlling for the inter-stroke distance (measured as the linear distance between the end point of the preceding stroke and the starting point of the successive stroke), radical boundary ISIs were significantly longer than logographeme boundary ISIs, which in turn are significantly longer than within logographeme ISIs. In addition, it was observed that shorter radical boundary ISIs were associated with high frequency characters, while longer radical boundary ISIs were associated with low frequency characters. Similarly, shorter logographeme boundary ISIs were associated with high frequency characters, while longer logographeme boundary ISIs were associated with low frequency characters. The within-logographeme ISIs, on the other hand, were not affected by character frequencies. Lau (2020b) explained the observations by suggesting that the longer boundary ISIs were attributed to the longer processing time needed to retrieve and/or plan for the subsequent writing units. Hence, it was suggested radicals and logographemes are units represented in the orthographic lexicon.

Figure 1 about here

In a follow up study, Lau (2020a) analysed the handwriting data of 151 phonetic compound characters, that the corresponding phonetic radicals were all free-standing characters such that the regularity of the target characters could be clearly defined, from the Database of Radicals in Written Chinese with Reliable Logographeme Boundaries (Lau, 2019a). The same main effect of boundary type (i.e. radical boundary ISIs > logographeme boundary ISIs > within logographeme ISIs) reported in Lau (2020b) was replicated. Furthermore, it was observed that the radical boundary ISIs decreased with character frequency and logographeme boundary ISIs decreased with radical frequency. Lau (2020a) suggested that the results indicated the participants' flexibility of using orthographic units of different grain sizes in their writing. It was suggested that the participants showed tendency to use larger grain size units as writing units, if they are of high frequency. However, if the large grain size units are of low frequency, the constituent small grain size units would be used instead.

Role of phonology in spelling Chinese

In the follow up study by Lau (2020a) described in the above, it was observed that the radical boundary ISIs were not only decreased with character frequency, but were also affected by the phonetic regularity of the characters. Specifically, radical boundary ISIs of regular characters were observed to be shorter than radical boundary ISIs of irregular characters. Lau (2020a) argued that the longer radical boundary ISIs associated with irregular characters were attributed to the competitions due to the mismatch of syllables associated with the irregular characters and their corresponding phonetic radicals. Hence, it was suggested that the reported significant phonetic regularity effect provided evidence to support the notion that phonology contributes to the writing of Chinese characters. It is, however, important to note that there is one major concern of this study by Lau (2020a). Given that an immediate copying task was used, the participants might have initiated the writing even before they finished the character recognition process. As a result, it is possible that the longer radical boundary ISIs associated with the irregular characters were resulted from the character recognition, as phonetic regularity has been reported to affect character recognition (e.g., Feldman & Siok, 1997;Lau et al., 2015; Perfetti & Tan, 1998; Zhou & Marslen-Wilson, 1999). In other words, it is possible that the phonetic regularity effect observed was resulted from a decoding process, instead of an encoding process.

Turning phonological code into orthographic code

Measures of total writing time, defined as the time difference between the onset of the first stroke and the offset of the last stroke of writing, were also included in studies of writing-to-dictation of Chinese. Lau (2021) observed that the total writing time of characters decreased with character frequency, and increased with number of strokes. Besides, it was further observed that longer total writing time was associated with low frequency characters with lots of homophones. This was attributed to the conflicts due to the process of selection of target orthographic forms from other distractors sharing the same syllables. Given that none of semantic variables are significant in predicting the total writing time in this experiment, the result may suggest different time course of the semantic and the non-semantic pathways of writing-to-dictation in Chinese. However, using a large-scale study, Wang (2020) found different results. Similar to the findings of Lau (2021), it was reported that the total writing time were predicted by stroke number and other exposure-related variables, including character frequency, age-of-acquisition and familiarity, but not semantic-related variables, such as imageability and concreteness. However, it was observed that total writing time was not affected by homophone density. It is noteworthy the total writing time in Wang (2020) was measured as the time difference between the onset of the first stroke of writing and the time the participants pressed a button to submit the product of writing of each trial, which is slightly different from the one measure by Lau (2021). Nevertheless, it is clear that the conflicting results reported in Lau(2021) and Wang (2020) made it inconclusive regarding the question of whether the homophonous characteristics of Chinese also affect the total writing time or not.

One issue about the use of total writing time is that it is a collection of a lot of ISIs, and also the time of writing individual strokes, of the entire character writing process. Given that different locations of ISIs are affected by different measures and reflected different cognitive processes involved in writing (Lau, 2020a; 2020b), total writing time probably is a product of a lot of processes added together. Hence, it may not be an ideal measure to investigate how individual cognitive processes affect writing. Future studies may want to use other measures of writing fluency, such as ISIs, average velocity of stroke writing (e.g. Zhang & Feng, 2017) and velocity peaks (e.g. Roux et al., 2013) to study how the central processing cascade to the peripheral processing in writing-to-dictation of Chinese.

Investigating Chinese spelling – what about children?

Thus far, most of the studies reviewed focused on Chinese spelling among mature writers. In fact, few studies using pen and tablets have been conducted to study the Chinese spelling among developing writers. Theories of statistical learning suggest that children implicitly acquire the statistical patterns that exist in orthographies and apply the statistical regularities to their spellings (e.g. Lee & Tong, 2020; Mano, 2016; Treiman & Kessler, 2006). Therefore, investigating the acquisition patterns of children should help to inform how children master the encoding process of orthographic output.

In a study using pseudo-characters constructed by combining semantic and phonetic radicals, Lau (2019b) instructed primary school children to perform in an immediate copying task. Similar pattern of longer boundary ISIs than within-logographeme ISIs was observed, after controlling for ISD. In addition to this, it was reported that ISIs decreased with logographeme frequency among grade 1 children, while ISIs decreased with both radical frequency and logographeme frequency among grade 5 children. Similarly, Lau (2019b) suggested that the boundary effect observed was attributed to the longer processing time needed to retrieve and/or plan for the subsequent writing units. In addition, the significant logographeme frequency effect was attributed to more proficient in the execution of graphic motor patterns associated with higher frequency logographemes. Hence, it was suggested that young children showed tendency to use smaller units in their writing, while older children are more flexible in using both small and big units in their writing. Nevertheless, it is important to note that Lau (2019b) used pseudo-characters, which are unknown to all children participants, as stimuli in the experiment. This might have exaggerated the logographeme and radical effects as it became legitimate for the children participants to copy the stimuli using a decomposed approach.

Another approach of observing the acquisition patterns of children in Chinese spelling is to observe the errors produced before children can master the encoding process of orthographic output. By observing the errors produced by children, it allows us to hypothesize the pathways they have to go through before they master the processing.

In Table 1, some examples of writing errors produced by children[2] are presented. In the following, the potential corresponding disruptions with reference to the central and peripheral processing of Chinese writing associated with each error were discussed.

Table 1 about here

Example 1 shows a character substitution error observed in a writing-to-dictation tasks. In this example, the error production shares the same syllable with the target character. This type of homophone substitution errors observed in writing-to-dictation tasks is one of the most common type of errors observed, even among mature writers. One possible explanation of this error is that it was originated from the mis-recognition of the target orthographic forms, potentially due to insufficient support from semantic system. Alternatively, it is also possible that the target orthographic form was not available. Hence, a homophone is legitimately selected to fulfil the requirements of a writing-to-dictation task.

Example 2 is another character substitution error. In this example, the error production shares the same meaning with the target character. Actually, the two characters

[2] All children were reported by their parents to be struggling in learning to write Chinese. They were accompanied by their parents to the Speech Therapy Unit of the Hong Kong Polytechnic University to seek for speech therapy services. The data came from an ongoing study that documents errors produced by children learning to write Chinese characters.

are frequently combined together to form a compound word 掠奪 [leok6 dyut6] <robbery> with a coordinative morphosyntactic structure. The substitution error, therefore, may be due to a confusion between the orthographic forms of the two characters and subsequently leading to a "selection error". Furthermore, the confusion is possibly attributed to insufficient support from the phonological system. Again, alternatively, it is also possible that the error was a legitimate written response using an orthographic form associated with meaning to fulfil the task requirement.

Example 3 shows a radical substitution error. It is suggested that this error possibly indicated an unconsolidated orthographic representation acquired. Since the replaced radical 虫 is the semantic radical of the target character, it is also possible that the error indicated insufficient support from the semantic system at the radical level.

Example 4 shows a logographeme substitution error. Just like Example 3, the error possibly indicated an unconsolidated orthographic representation acquired. It is further hypothesized that this substitution error indicated the (over-)reliance of logographemes instead of radicals as writing units. If the phonetic radical 洛 [lok6] was used as the writing unit, the support from phonological system should help to avoid this error.

Overall, these errors indicated that the need for children to develop good lexical quality (Perfetti & Hart, 2002) in the process learning to become mature writers. Specifically, to achieve accurate writing, consolidated orthographic representations at both character and radical levels that are well-connected with the corresponding syllables in the phonological domain and semantic features in the semantic system are needed.

Example 5 and Example 6 show errors of allograph selections. Both the target semantic radical ⻊ <foot-related> and the target phonetic radical 足 [zuk1] are originated from the character 足[zuk1]<foot>. Hence, the two radicals are considered as allographic forms corresponding to the same abstract radical identity (Li et al., 2020). Therefore, the two errors possibly indicated the incorrect selection of allographs or the lack of awareness of the positional-specific allographic forms associated with the abstract radical identity in the peripheral processing of writing.

Example 7 and Example 8 are not exactly errors. They were characters written by the same child in one session in a delayed copying task. In each trial of the task, a character was first displayed for five seconds. Upon the disappearing of the target, the child was required to write the character just shown. In terms of accuracy of writing, both items should be considered correct trials. However, as indicated by the stroke order number, different stroke sequence was used to write the top right logographemes (stroke order 7 – 9). It is hypothesized that the different stroke sequence was attributed to indefinite (or unavailability of) graphic motor patterns of the corresponding logographeme. Although indefinite graphic motor patterns of writing units may not necessarily always lead to errors in writing, it is speculated that Chinese character writing that depends heavily on "improvisation" of graphic motor patterns is error prone. Besides, it is expected that more cognitive resources are needed to support the "real-time" improvisation of graphic motor patterns to write the targets, hence an undesired sluggish writing performance will inevitably be resulted. Future work is needed to warrant this claim.

Summary

Overall, the cognitive mechanism of Chinese spelling evident from handwriting measures obtained using pen and tablets are summarized in Figure 2.

Figure 2 about here

In Figure 2, the cognitive construct of Chinese characters writing is categorized into the central and the peripheral processes. The framework of the central processes follow the classic "triangle" model suggested by Seidenberg and McClelland (1989), in which lexical information is represented in the semantic, phonological and orthographic domains. In the orthographic domain, characters, radicals and logographemes are represented (Chen & Cherng, 2013; Lau 2020a; 2020b). The direction of information flow depends on the task requirements. For example, in a writing-to-dictation task, syllables represented in the phonological domain will be first recognized. Subsequently, the target syllable can directly activate the corresponding orthographic representations of characters (Han et al., 2012) and phonetic radicals (Wang et al., 2020), which is called the non-semantic pathway. Besides, orthographic representations of characters (Lau, 2021; Wang et al., 2020) and semantic radicals (Yum et al., 2022) can be activated via the corresponding semantic features in the semantic system, which is called the lexical-semantic pathway. Similarly, in a picture naming task, semantic features in the semantic system will be first identified. Subsequently, the corresponding characters and semantic radicals may be activated directly or via the corresponding syllables in the phonological domain, following the suggestions of Qu et al. (2011) and Qu et al. (2016).

Following the notion of cascaded processing suggested (e.g. Lau, 2020a; Qu et al., 2011), information flows from one level to another before the former process is completed. Therefore, it is likely that the orthographic representations of the target characters, the constituent radicals and logographemes will all receive activation during the computation. The relative ease for certain units to be fully activated probably depends on the frequencies of the corresponding units (Lau, 2020a). For high frequency radicals, proceeding directly to peripheral processing is possible even without fully activating the constituent logographemes, whereas for low frequency radicals, subsequent peripheral processing will be carried out via the constituent logographemes.

The peripheral processes begin with allograph selection, which is then followed by the retrieval of the corresponding graphic motor patterns. The availability of the graphic motor patterns of orthographic units depends on their corresponding frequencies. Graphic motor patterns of high frequency large grain size units are available. For low frequency large grain size units, they have to be written via the graphic motor patterns of the corresponding small grain size units, following the predictions of Lau (2020a; 2020b). Finally, motor execution of the writing will be conducted based on the retrieved graphic motor patterns.

Educational Implications

What we learnt about Chinese character writing so far has important implications on education. First, in traditional Chinese classrooms, penmanship drill practice was commonly used. Yet, there were queries across the years that concern the necessity of such practice exercise. Theoretically, as indicated in Figure 2, it is expected that penmanship exercises should be directly relevant to the objective of strengthening the graphic motor patterns in handwriting. Nevertheless, traditional classroom penmanship exercise usually targets on copying the entire characters, or even multi-character words, which mismatches with the cognitive construct suggested in Figure 2, in which graphic motor patterns of small instead of large grain size units are represented. For most typical learners, copying large grain size units can probably serve as a top-down training that allows the achievement of the objective of strengthening of graphic motor patterns of small grain size units. For struggling learners, bottom-up training, which focuses on copying small grain size units and gradually introducing large grain size units may be needed. Besides, future studies will also be needed to investigate the optimal number of practice trials to maximize the acquisition of the graphic motor patterns without overwhelming the learners.

Next, as illustrated in Figure 2, each lexical item consists of an orthographic form, a phonological form and the corresponding semantic features. Therefore, when educators introduce a lexical item, it is necessary to emphasize all three components. Nevertheless, introducing forms in isolation is not recommended as introducing forms out of contexts requires individual learners to rely solely on their rote memory to acquire the forms, which will easily overwhelm the learners. Instead, introducing the syllable-phonetic radical relations and the meaning-semantic radical relations (e.g. Ho et al., 2003) through either explicit instructions (e.g. Lam & McBride-Chang, 2013; Packard et al., 2006) or implicit instructions governed by statistical learning principles (e.g. Tong & McBride, 2014; Tong et al., 2020) are expected to result in better generalization. Finally, to introduce the meanings of characters, instead of only offering the verbal descriptions of the meanings, it is suggested that educators can vary the word contexts (e.g. 點燃 <ignite> , 燃燒 <combustion> and 燃料 <fuel> for the target character 燃 <burn>) and/or sentence contexts that the target characters occur when they introduce characters. The varied word contexts are expected to highlight the morphological features of the target characters and the varied sentence contexts are expected to highlight the unique semantic features of the target characters (e.g. Plante et al., 2014).

Future directions

There are at least three future directions identified.

First, as described in the above, most studies that used pen and tablets to investigate Chinese spelling were conducted on mature writers. Given the errors and the corresponding hypothesized potential disruptions in the central and peripheral processing described in the above, it is suggested that more studies to investigate how children learn to spell Chinese are needed. For instance, it has been hypothesized that the error Example 3 in the above is attributed to insufficient support to the radical level from the semantic system. Comparing the writing-to-dictation RTs of characters with high and low semantic radical transparency among children should help to warrant the hypothesis. Similarly, it has been hypothesized that the error Example 4 in the above was attributed to insufficient support to the radical level from the phonological system. Comparing the radical boundary ISIs of regular and irregular characters using character copying and/or delayed copying tasks on children should be relevant.

Another future direction of research concerns the peripheral processing of writing among children. A recent study by Wiley and Rapp (2021) has emphasized the importance of handwriting experience on literacy learning. Specifically, it was suggested that modality-specific representations, including visual, motor and phonological, will help to strengthen the amodal symbol identity of orthographic units in literacy learning. If this is true, children having indefinite graphic motor patterns of orthographic units, as in Example 7 & 8 in Table 1, should demonstrate more struggles in their learning of the abstract symbol identity of radicals and logographemes, and consequently show poor performance in learning to read and write Chinese. Therefore, it is suggested that investigating the significance of having definite graphic motor patterns in writing, measured as the consistency of stroke sequence of writing, in learning to spell Chinese among children should help to warrant the hypothesis.

Finally, it is suggested that handwriting measures can also be applied on individuals learning Chinese as a foreign language (CFL). A preliminary study by Lau et al. (2022) documented that in a delayed copying task, CFL high achievers demonstrated the flexibility in using both large and small grain size writing units, while low achievers demonstrated the heavy reliance of small grain size writing units only. Lau et al. (2022) suggested that the difference was attributed to better orthographic knowledge among the high achievers. Future studies using similar design are recommended to verify their claims.

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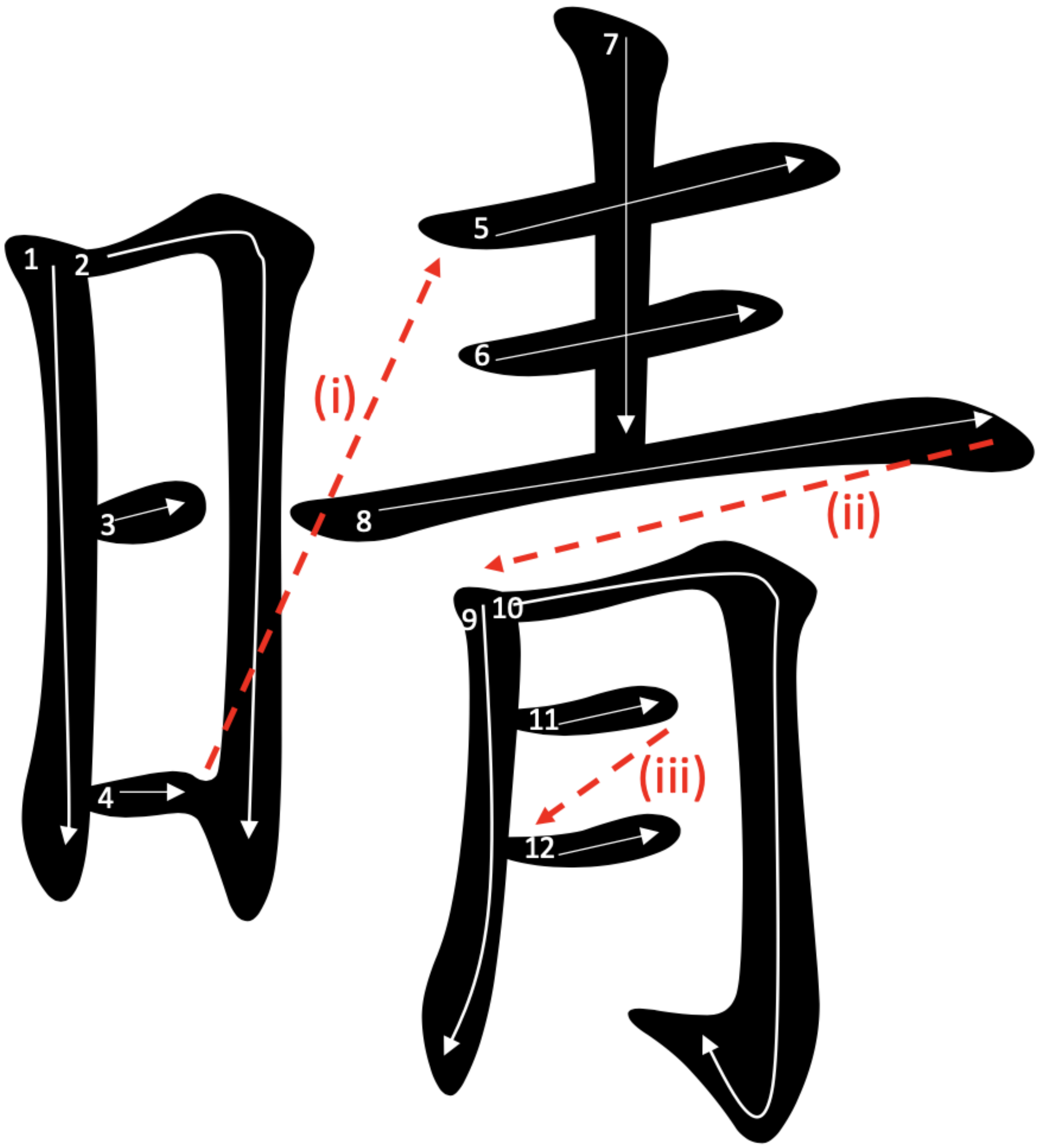


Figure 1. Example of different inter-stroke intervals (ISIs) illustrated using the character 晴 [cing4] <sunny> which consists of the semantic radical 日 <sun> on the left and the phonetic radical 青 [cing1] on the right. The phonetic radical 青 can be further broken down into the top logographeme (from the 5th to the 8th stroke) and the bottom logographeme (from the 9th to the 12th stroke). (i) ISI at radical boundary, (ii) ISI at logographeme boundary, and (iii) ISI within logographeme. The digits denote the writing sequence.

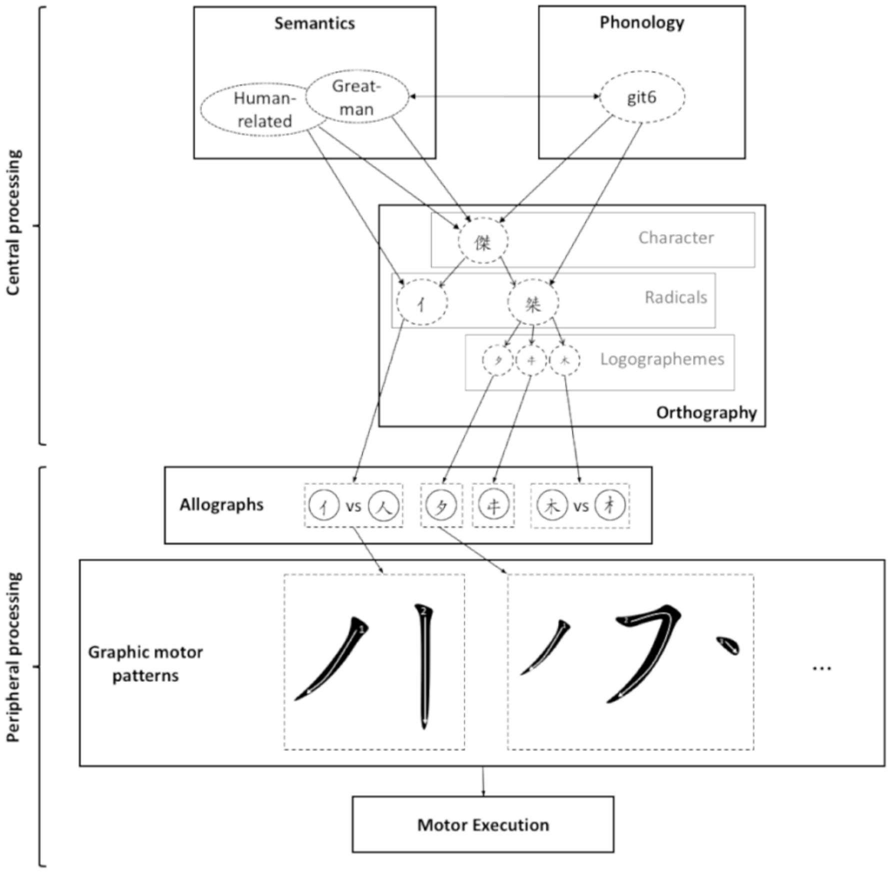
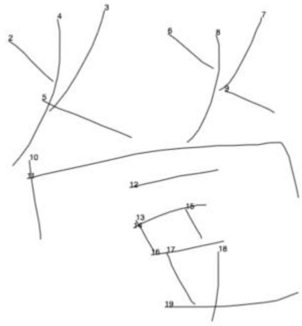
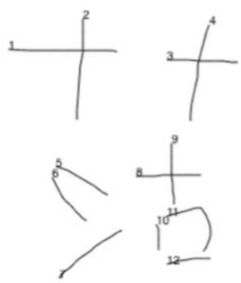
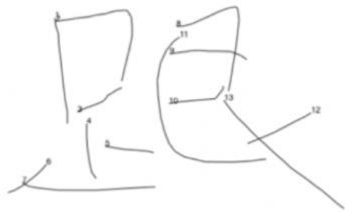
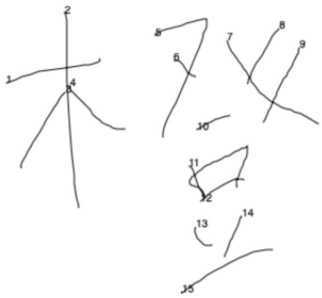
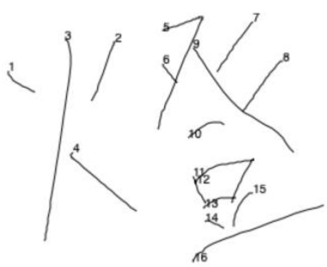


Figure 2. The central and peripheral processing of Chinese character writing.

Table 1. Writing errors and their corresponding targets observed from children.

	Target character	Error production
Example 1	落 [lok6] <fall>	
Example 2	奪 [dyut6] <seize>	
Example 3	螢 [jing4] <firefly>	
Example 4	落 [lok6] <fall>	

Example 5	捉 [zuk1] <catch>	
Example 6	跟 [gan1] <follow>	
Example 7	橙 [caang2] <orange>	
Example 8	燈 [dang1] <light>	

Note. Digits in the handwriting productions denote the order of stroke sequence and the onset positions of the corresponding strokes.