Representations of grapho-motor patterns unique to Chinese character writing: Evidence from a patient with mirror writing

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Abstract

This study investigated the grapho-motor patterns used in writing Chinese characters. A Chinese patient, CSC, who demonstrated post-brain-injury mirror writing, was recruited. In Experiment 1, non-mirrored writing responses were obtained when CSC was instructed to copy asymmetrical non-verbal symbols and pictures. Resembling the patterns observed in a patient's writing reported in a previous study, it was hypothesized that CSC's mirror writing was a result of untransformed preserved grapho-motor patterns. In Experiments 2 and 3, CSC was further instructed to copy real Chinese characters, pseudo-characters with authentic radicals and logographemes (i.e., stroke clusters that frequently occur in radicals), and Hangul characters with stroke clusters resembling the shapes of authentic logographemes. The results showed that CSC demonstrated mirror writing only when authentic Chinese orthographic units were involved. Non-mirrored writing responses were obtained from stimuli without authentic Chinese orthographic units. In sum, CSC's performance supported the existence of grapho-motor patterns of Chinese orthographic units represented in the brain. Theoretical implications were discussed.

Keywords: Chinese; mirror writing; dysgraphia

Background

Writing is a unique means of communication in which a person presents his/her ideas in textual formats that can be transferred to a potentially unlimited number of communicative partners beyond time and space. Given its importance, research on the process of generating orthographic codes from ideas has received much attention. The architecture of the writing process can be divided into central and peripheral processing (Bonin, Méot, Lagarrigue, & Roux, 2015; Ellis and Young, 1996). Central processing includes orthographic long-term memory, conversion from phonology to orthography, and orthographic short-term memory. Peripheral processing, on the other hand, includes allograph selections, graphic motor pattern selections, and the execution of graphic motor patterns. In this study, the storage of graphic motor patterns in the peripheral processes involved in writing Chinese characters was investigated.

Chinese is a morphosyllabic language in which each basic orthographic unit, or character, is mapped onto one syllable and one morpheme (Hoosain, 1992). For example, the character 金 corresponds to the syllable [gam1][1] and the morpheme <metal>. One major group of Chinese characters, called phonetic compounds, contains radicals that give clues to sound and meaning. For example, the character 鎂 [mei5] <magnesium> contains the semantic radical 金 <metal-related> that gives clues to meaning and the phonetic radical 美 [mei5] <beautiful> that gives clues to phonology.

Various psycholinguistic studies have demonstrated that phonetic radicals are involved in the recognition of Chinese phonetic compound characters (e.g., Hue, 1992; Lau, Leung, Liang, & Lo, 2015; Weekes & Chen, 1999). Particularly, it has been reported that

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

low-frequency regular phonetic compound characters, those that share the same syllables with their corresponding phonetic radicals, have significantly shorter reading latencies than irregular ones. Moreover, evidence of processing phonetic radicals in character recognition has also been observed in neural responses in event-related potential (ERP) experiments (e.g., Lee et al., 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 compound characters.

Similarly, previous studies have also documented the role of semantic radicals in the processing of Chinese phonetic compound characters (e.g., Feldman & Siok, 1999; Li & Chen, 1999; Zhou & Marslen-Wilson, 1999). In general, it has been reported that low-frequency phonetic compound characters 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 the hypothesis that 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 compound characters 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 premorbid writing abilities (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 additions, substitutions, and deletions of strokes, phonetic radicals, and semantic radicals, indicating that apart from strokes, phonetic and semantic radicals are involved as functional processing units in the Chinese writing process. Particularly, Law et al. (2005) observed that the semantic radical substitution errors produced by their 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 with semantic deficits who 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.

Besides semantic and phonetic radicals, another type of sub-lexical unit observed in writing Chinese characters has been reported in the literature. A study conducted by Law and Leung (2000) 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", "土", and "口" in the radicals "糹" and "吉", respectively, as shown in Figure 1). Similarly, in a study by Han, Zhang, Shu, and Bi (2007), another stroke patient produced similar errors of logographeme deletions, substitutions, and transpositions. These studies 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 of 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. Thus far, previous studies on Chinese writing have mostly focused on the investigation of central processing. Little, however, has been done to explore the peripheral processes of Chinese writing. In the current study, the performance of a patient who produced mirror writing errors was investigated to fill this gap.

Mirror writing refers to the production of words or individual letters in the reverse direction (Gaddes, 1980; Lebrun, Devreux, & Leleux, 1989). Mirror writing has been reported among young children who are beginning learners of writing (Cornell, 1985; Cubelli & Della Sala, 2009) and children with developmental writing difficulties (Wang, 1986), as well as brain-injured patients (Angelillo, Lucia, Trojano, & Grossi, 2010; Balfour, Borthwick, Cubelli, & Della Sala, 2007; Rodriguez, Aguilar, & Gonzalez, 1989).

Although there are exceptions (Angelillo et al., 2010), mirror writing observed among brain-injured patients is usually associated with left non-dominant hand writing (Balfour et al., 2007), as patients who are right-handed premorbid are forced to use their left hand to write due to right hemiplegia or hemiparesis resulting from left-hemisphere strokes. The three most commonly referenced explanations for mirror writing include the hypotheses of mirror engram disinhibition (Orton, 1928), spatial disorientation (Heilman, Howell, Valenstein, & Rothi, 1980), and the failure of the automatic spatial transformation of the grapho-motor patterns required when the non-preferred hand is used for writing (Angelillo et al., 2010; Critchley, 1928). The first two hypotheses are usually rejected if patients demonstrate no right-left disorientation and make no mirrored errors in non-verbal tasks. Under the last hypothesis, the grapho-motor patterns of writing, in the form of motor spatial sequences, are stored in the dominant hemisphere of the brain and are employed when the dominant hand is used for writing. For example, when a right-handed person attempts to write an asymmetrical letter “F”, a vertical stroke will be written, followed by two horizontal strokes away from the body, or body midline according to Rodriguez et al. (1989). If the same right-handed person attempts to apply the same spatial motor pattern (i.e., a vertical stroke followed by two horizontal ones away from the body) without spatial transformation to write the letter "F" using the left hand, a mirrored "F" will be the result.

In the current study, CSC, a brain-injured patient who produced mirror writing errors, was tested using a number of different tasks. In Experiment 1, CSC was tested using a non-verbal symbols copying task to rule out the mirror engram disinhibition (Orton, 1928) and the spatial disorientation (Heilman et al., 1980) hypotheses. In Experiment 2, CSC was tested using a copying task with a stimuli set that included real characters, pseudo-characters with real radicals, and pseudo-radicals with real logographemes. Finally, in Experiment 3, CSC was tested using a copying task with a Hangul stimuli set that included unauthentic logographemes organized in left-right and top-bottom configurations resembling those of Chinese characters. Mirror writing errors and any sluggish writing responses in the different experiments were recorded to determine the types of grapho-motor patterns represented in the brain.

Experiment 1

Participant

CSC, a 56-year-old Cantonese Chinese female patient who had suffered from a stroke 30 months before this experiment, was recruited. CSC was right-handed premorbid but started to use her left hand for writing due to right-sided hemiplegia caused by a left-hemisphere stroke, which resulted in CSC producing mirrored characters. CSC's education level was junior secondary school, and she was a housewife before the stroke. An initial assessment using the Cantonese version of the Western Aphasia Battery (CAB) (Yiu, 1992) revealed an AQ score of 96.2, resulting in a diagnosis of mild anomic aphasia. No visual or hearing impairment was reported.

Materials and tasks

A comprehensive follow-up assessment was conducted after CSC was referred to us for a detailed assessment of her reading and writing problems using the stimuli set from Law et al. (2005). The following tasks were included:

Verbal semantic task:

(1) a synonym judgment task in which CSC had to decide whether two aurally presented words had a similar meaning

Non-verbal semantic tasks:

(1) the Birmingham Object Recognition Battery (BORB)—Test 7 (minimal feature view task), Test 8 (foreshortened view task), Test 10 (object decision task), and Test 12 (association match task) (Riddoch & Humphreys, 1993); and
(2) the Pyramid and Palm Trees Test (PPTT) (Howard & Patterson, 1992)

Auditory comprehension:

(1) spoken word picture matching task, with a semantic and an unrelated distractor for each item

Picture naming:

(1) oral and written naming using black-and-white drawings taken from Snodgrass and Vanderwart's (1980) picture set

Reading:

(1) written homophone identification with semantic, tonal, orthographically similar, and phonologically similar distractors;
(2) reading aloud monosyllabic words; and
(3) written word picture matching task, with a semantic and an unrelated distractor for each item

Lexical decision task:

(1) CSC had to judge the lexicality of a total of 32 real items and 32 unreal items constructed by (a) inserting strokes, (b) omitting strokes, (c) substituting logographemes, or (d) transposing logographemes in the real counterparts, presented in random order

Writing:

(1) Writing-to-dictation task

A non-verbal items copying task was carried out to examine whether CSC might also demonstrate mirror writing errors in copying non-verbal items. A total of 12 asymmetrical pictures and 12 asymmetrical lined symbols were selected. A 7-inch tablet with a resolution of 1820 x 1200 and refresh rate of 60 Hz was used in this study. The tablet was Quad-core with 2.20 GHz processing speed and ran the latest Android 4.1.1 version. The tablet was installed with an Android application that controlled the display of stimuli and recorded the written responses of the participant. In each of the randomly-ordered trials, a target was shown on the top-left corner of the tablet screen. CSC was instructed to copy the item using a stylus pen.

Results and Discussion

Comprehensive assessment

Table 1 shows CSC's performance on each of the tasks in the comprehensive assessment. CSC demonstrated high accuracies in auditory (126/126) and written (126/126) word to picture matching tasks, suggesting that she had intact spoken and written comprehension of object names. Her close-to-perfect performance in the reading tasks suggests that her orthographic input lexicon was largely preserved. In addition, her good performance on the BORB tests, the PPTT, and the synonym judgment task also indicated a relatively intact semantic system.

Insert Table 1 about here

Regarding language expression, CSC's score on the oral naming task (82.3%) was lower than that of the control participants (average = 93%) reported by Law (2007), which is consistent with CSC's diagnosis of mild anomia aphasia according to the CAB results. On the other hand, CSC's score on the written naming task (83.1%)[2] was within the normal range compared to that of the lower education group (average = 66%) found in Law (2007), which indicated relatively good writing abilities. Nevertheless, CSC's relatively poorer performance in the writing-to-dictation task (63%) compared to that of the lower education group (average = 74%) in Law (2007) indicated some degree of dysgraphia even when mirror writing responses were accepted as correct trials.

Non-verbal items copying task

A complete set of CSC's output can be found in Appendix A. The results showed that CSC demonstrated no mirror writing errors in copying the asymmetrical pictures and symbols. Overall, CSC's close-to-perfect performance on the lexical decision task, with a perfect score on rejecting pseudo-characters with logographeme transpositions, indicated intact spatial perception. Moreover, the absence of mirror writing errors in copying the asymmetrical pictures and symbols suggests that CSC's mirror writing responses were associated with verbal items only. Therefore, the mirror engram disinhibition (Orton, 1928)

[2] CSC produced mirror writing errors only in the written naming task and the writing-to-dictation task. The scores reported here were based on the mirror images in her written production.

and the spatial disorientation (Heilman et al., 1980) hypotheses were ruled out. Hence, CSC's persistent mirror writing errors were probably due to a failure in the automatic transformation of preserved grapho-motor patterns when writing with her left hand (Angelillo et al., 2010). What remains unclear is whether CSC used the grapho-motor patterns of strokes, logographemes, radicals, and characters when she wrote.

Given that CSC's mirror writing originated from untransformed preserved grapho-motor patterns, an investigation of the grapho-motor patterns she used in writing based on her performance on copying various types of stimuli was warranted. For example, if she solely used the grapho-motor patterns of characters, copying pseudo-characters should not have resulted in mirror writing errors because of the absence of corresponding grapho-motor patterns; however, if she did attempt to copy the targets in a mirror-writing format, a more sluggish overall handwriting performance would be expected. Similarly, if she solely used the grapho-motor patterns of radicals, copying the real and pseudo-characters constructed by combining radicals in their legal positions should have resulted in mirror writing errors; however, if she copied pseudo-radicals constructed by combining logographemes, an absence of mirror writing errors or the presence of sluggish mirror writing would be expected. In Experiment 2, CSC was instructed to copy character items constructed specifically for this investigation.

Experiment 2

Materials and task

A character copying task was prepared. Three different types of stimuli, including (A) 40 real characters, (B) 40 pseudo-characters constructed by shuffling the semantic and phonetic radicals of the characters in (A), and (C) 40 non-characters constructed by combining the semantic radicals in (A) and the pseudo-radicals constructed by swapping the top and bottom components of each pair of phonetic radicals in (A). Examples and the properties of each type of stimulus are given in Table 2.

Insert Table 2 about here

The task procedures were similar to that of the copying task in Experiment 1. In each of the randomly-ordered trials, a target was shown on the top-left corner of the tablet screen. CSC was encouraged to write in her "usual and comfortable" way using the stylus pen. In addition to the written output, the total writing time, measured as the time difference between the onset of the first stroke and the offset of the last stroke, that CSC spent on each character was also collected. The task took two hours to complete.

Results and Discussion

CSC's written output for the three types of stimuli can be found in Appendix B. The results showed that CSC produced mirror writing for all the stimuli in the task. Table 3 summarizes the average total writing time for each of the three types of characters, and as can be seen, no significant difference in the total writing time was found ($p > 0.1$).

Insert Table 3 about here

The comparable total writing time of the three types of characters indicated no sluggish handwriting performance in copying the Type B and Type C characters. Moreover, the presence of mirror writing for all three types of characters suggests that CSC's performance in Experiment 2 was supported by the preserved grapho-motor patterns in Chinese writing. There are three possible explanations for the results obtained. First, it is possible that CSC's mirror writing in this experiment was supported by the preserved grapho-motor patterns of characters, radicals, and logographemes, as she was capable of using the grapho-motor patterns of units of different grain sizes flexibly. Alternatively, it is possible that CSC only applied the preserved grapho-motor patterns of logographemes in this experiment, since all the logographemes in the three types of stimuli were authentic. Finally, it is also possible that CSC used the grapho-motor patterns of strokes when she copied the stimuli in this experiment. To investigate the likelihood of the last possibility, copying the Korean alphabet, called Hangul, was the task chosen for Experiment 3.

There are 19 consonants and 21 vowels in Hangul, each with a unique orthographic form. Hangul was selected because many of the orthographic forms of Hangul consonants and vowels resemble the logographemes in traditional Chinese (e.g., ㅅ and ㄹ in Hangul resemble the logographemes 人 and 己 in traditional Chinese). Moreover, the configurations of Hangul syllables, usually aligned in left-right and/or top-bottom structures, also resemble those of traditional Chinese characters. Nevertheless, there are some Hangul orthographic forms (e.g., ㅌ and ㅒ) without orthographic-equivalents in traditional Chinese. Hangul characters, therefore, can be constructed in configurations identical to traditional Chinese characters but with unauthentic logographemes. If CSC used the grapho-motor patterns of strokes instead of the grapho-motor patterns of logographemes in copying the Hangul characters, the absence of mirror writing errors or the presence of sluggish handwriting performance would be expected.

Experiment 3

Materials and task

CSC reported that she had not learned Hangul characters before, of which 40 Hangul characters were constructed by putting the consonants and vowels in their legal positions. The average number of strokes was 9.425 (SD = 2.275). Identical to the procedures of the copying tasks in Experiments 1 and 2, in each of the randomly-ordered trials, a target was shown on the top-left corner of the tablet screen. CSC was encouraged to write in her "usual and comfortable" way using the stylus pen. In this task, the written output and the total writing time CSC spent on each character were also collected.

Results and Discussion

The written output for all the stimuli can be found in Appendix C. The results showed that CSC produced mirror writing errors for the first two items in the task, and then shifted to non-mirror writing starting with the third item. The average total writing time was 12.599 seconds (SD = 3.160). The results of the one-way ANOVA [$F(3, 156) = 48.21$, $p < .001$], followed by post-hoc Bonferroni tests, indicated a significant difference in the total writing time in copying Hangul characters compared to that of the three types of stimuli in Experiment 2 ($p < .001$).

Overall, the dominance of both non-mirror writing and longer total writing time in CSC's copying of Hangul characters were consistent with the prediction regarding copying without the support of preserved grapho-motor patterns. Figure 1 displays CSC's copying output for one of the target Hangul characters as an example. The order of the stroke sequence CSC used in the copying task is indicated next to the onset position of each stroke. The opposite directions of the second and the seventh strokes and the different ways of writing the unit "ㄹ" further confirmed that CSC used random grapho-motor patterns when she copied the Hangul characters. Therefore, the possibility that CSC's mirror writing was supported by untransformed grapho-motor patterns of strokes was rejected.

Insert Figure 1 about here

General Discussion

The aim of the current study was to investigate the types of grapho-motor patterns individuals use in writing Chinese characters. The mirror writing patterns of a brain-injured patient were reported. Overall, CSC reported that she was aware of her mirror writing problem. When verbal instructions were given, CSC was able to produce non-mirrored writing responses, although the overall clarity and speed of writing was sacrificed. CSC's persistent mirror writing evident 30 months after the stroke was consistent with the patient G.F.'s patterns described in Angelillo et al. (2010). The absence of spatial disorientation and correctly oriented non-verbal items observed in CSC's writing suggested a failure in the automatic transformation of grapho-motor patterns when writing with her non-dominant hand. The persistent mirror writing in CSC's copying of pseudo-characters and pseudo-radicals in Experiment 2, together with the dominance of non-mirrored writing responses in copying Hangul characters constructed in configurations identical to traditional Chinese characters but with unauthentic logographemes in Experiment 3, suggested that specific grapho-motor patterns unique to Chinese orthographic units were represented in the brain.

These grapho-motor patterns unique to Chinese orthographic units probably resulted from mandatory heavy penmanship drills, either in the format of copying monocharacter or multicharacter words, in Chinese classrooms starting at early grade levels (Chan, Juan, & Foon, 2008). Given the overall high orthographic complexity of Chinese characters, grapho-motor patterns of stroke clusters are considered essential in supporting the more automatic conduction of handwriting in Chinese. The existence of grapho-motor patterns unique to Chinese orthographic units is also consistent with a previous report that Chinese children start to use stable stroke sequences in writing Chinese characters in Grade 1 (Law, Ki, Chung, Ko, & Lam, 1998). What remains unclear is whether there are grapho-motor patterns in Chinese orthographic units of various grain sizes, whether one can flexibly apply different grapho-motor patterns in writing, and whether there are grapho-motor patterns of small grain size logographemes only that, in combining them, serve the writing of all larger grain size units.

In a previous study by Han et al. (2007), their patient demonstrated a word length effect measured in terms of the number of logographemes as well as dominant logographeme substitution errors in a delayed copying task. Based on their observations, Han et al. (2007) concluded that the logographemes were the units processed in the orthographic output buffer that temporarily stored orthographic units output from the orthographic lexicon while the units were pending motor execution in handwriting (Caramazza, Miceli, Villa, & Romani, 1987). The notion of "grapho-motor patterns of small grain size logographemes only" found in the current study is more compatible with Han et al.'s (2007) conclusion. Given that writing bigger grain size units can always be achieved by combining the grapho-motor patterns of small grain size units, one advantage of the "small grain size only" notion is that it avoids redundant representations in the brain. In fact, CSC's overall comparable total writing time across all three types of stimuli in Experiment 2 provided some support for this notion. Alternatively, if the "various grain sizes available" notion was found, CSC should have copied Type A and Type B characters faster than Type C characters, assuming that the storage of the grapho-motor patterns of the bigger units was facilitated even though it was redundant. However, based on the insignificant difference in total writing time observed among the three types of characters, the results of the current study favor the "small grain size only" notion. Future studies that make use of handwriting measures in the investigation of Chinese character writing among normal individuals may be useful to verify this claim.

Conclusion

The current study explored the types of grapho-motor patterns used in writing Chinese characters by observing CSC's performance on copying characters with authentic and unauthentic orthographic stroke clusters, which resulted in persistent non-dominant hand mirror writing caused by a brain injury. CSC's non-mirrored writing responses in copying non-verbal symbols and pictures, together with the absence of spatial disorientation, were evidence supporting CSC's use of untransformed preserved grapho-motor patterns in her mirror writing (Angelillo et al., 2010). In addition, the presence of mirror writing only in the copying of real characters and pseudo-characters with authentic radicals and/or logographemes, together with the absence of mirror writing errors in copying Hangul characters with unauthentic logographemes organized in typical left-right and top-bottom configurations resembling those of Chinese characters, were evidence supporting the existence of specific grapho-motor patterns unique to Chinese orthographic units represented in the brain.

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Disclosure statement

The authors have no conflict of interest to report.

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Table 1. CSC's performance on the comprehensive assessment.

Tasks	Result
Synonym judgment	90% (54/60)
Non-verbal semantic tests	
BORB[a]	
Test 7	100% (25/25)
Test 8	96% (24/25)
Test 10	100% (32/32)
Test 12	96.7% (22/23)
PPTT[b]	96.8% (31/32)
Auditory comprehension	
Spoken word-picture matching	98.4% (124/126)
Picture Naming	
Oral	82.3% (214/260)
Written[c]	83.1% (216/260)
Reading	
Written homophone identification	97.0% (63/65)
Monosyllabic word reading aloud	98.3% (177/180)
Written word-picture matching	98.4% (124/126)
Lexical decision task	
Real items	100% (32/32)
Unreal items with	
Strokes insertion	100% (8/8)
Strokes omission	87.5% (7/8)
Logographeme substitution	100% (8/8)
Logographeme transposition	100% (8/8)
Writing-to-dictation[c]	63% (171/273)

[a]Birmingham Object Recognition Battery (Riddoch & Humphreys, 1993).

[b]Pyramid and Palm Trees Test (Howard & Patterson, 1992)

[c]Accepting mirrored responses as correct

Table 2. Lexicality, authenticity of phonetic radicals and logographemes, and examples of each type of stimuli.

	Character types		
	A	B	C
N	40	40	40
Lexicality	Yes	No	No
Phonetic radical authenticity	Yes	Yes	No
Logographeme authenticity	Yes	Yes	Yes
Number of strokes			
Mean	14.48	14.35	14.35
S.D.	3.24	3.32	3.19
Examples	垮		
	瀉		

Table 3. Mean and standard deviation of total writing time of each type of stimuli.

	Character types		
	A	B	C
Mean copying time (second)	7.628	7.378	7.869
Standard deviation	1.704	1.709	2.221

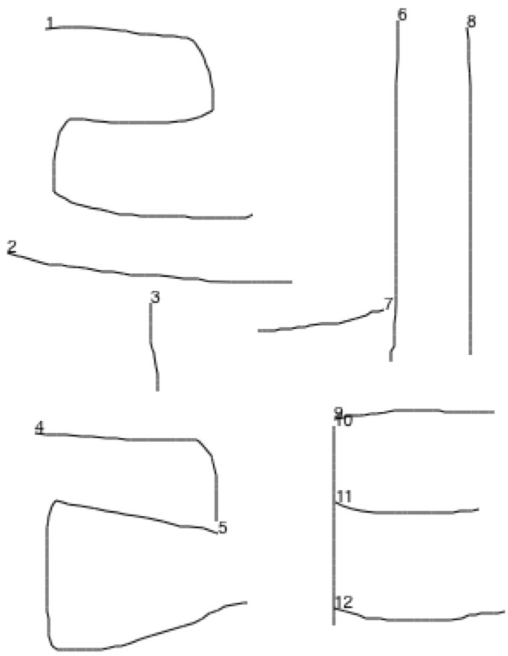

Figure 1. The written output of CSC's copying of the Hangul character "뤬". The order of stroke sequence was indicated next to the onset position of each stroke.