

Erratum to: Writing quality predicts Chinese learning

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Writing quality predicts Chinese learning

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Abstract To examine the importance of manual character writing to reading in a new writing system, 48 adult Chinese-as-a-foreign-language students were taught characters in either a character writing-to-read or an alphabet typing-to-read condition, and engaged in corresponding handwriting or typing training for five consecutive days. Prior knowledge of orthography and phonology was assessed before training. At the end of each training day, improved orthographic quality was assessed via increased skill in producing Chinese characters at both the component and global levels. In addition, pretests and posttests were administered at each training day, and the proportional changes were used as the measure of learning gains. Outcomes replicated earlier findings of improved phonological knowledge following pinyin-typing practice and improved semantic knowledge following handwriting practice. Improvement in handwriting quality played a significant role in predicting reading gains after controlling for prior knowledge.

Keywords Handwriting · Orthography · Reading acquisition · Chinese L2 learning

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Introduction

In skilled reading of Chinese, establishing a memory representation of an orthographic form (a character) in memory is the gateway to accessing a word's meaning and pronunciation through print (Perfetti, Liu, & Tan, 2005). In learning characters, writing characters should contribute significantly to acquiring an orthographic representation of the character, and thus writing characters should support reading characters. Indeed research with adult Chinese learners has established such a result (Guan, Liu, Chan, & Perfetti, 2011).

Beyond this kind of global effect—i.e., writing characters leads to better character reading—there is a need for evidence at a fine grain level; that is, if writing is establishing high quality lexical representations (Perfetti, 2007), then we should be able to observe direct effects between writing quality during learning and orthographic recognition. Accordingly, the purpose of the present study is to trace the acquisition of writing quality during character learning and identify the effects of this quality on later character reading.

For learners of Chinese from an alphabetic background, learning of characters may present distinctive challenges, because each character must be acquired as a unique form, even if other characters share one of its components. Accordingly we begin with some explanations of the character system and how it is learned.

Unique characteristics of learning to read and write in Chinese

In classroom handwriting practices, Chinese children begin writing by practicing individual strokes, then progress to radical (character subcomponent) writing, and finally to whole character writing (Qiu, 2000; Wu, Li, & Anderson, 1999). Eighty percent of modern Chinese characters consist of both semantic and phonetic radicals, which provide clues to character meaning and pronunciation (Feldman & Siok, 1997, 1999; Ho, Ng, & Ng, 2003), and repeated writing practice is commonly used to strengthen orthographic, semantic, and phonological associations (Guan et al., 2011). The theoretical rationale for this practice follows from the design principle of the writing system. For example, the Chinese pinyin (i.e., the alphabetic coding) “hao” (disregarding tones) corresponds to 67 Chinese characters with distinct meanings: hao1 (蒿) is a kind of plant, hao2 (蚝) has the meaning of oyster or fine hair, hao3 (好) refers to goodness and hao4 (好) refers to love of [something] such as love of learning. Thus, language-specific mapping between other types of representations in Chinese (e.g., strokes, radicals and tones) might be used for writing and word recognition. Indeed, literacy in Chinese emphasizes the role of strokes, radicals and whole characters in handwriting (Guan et al., 2011).

The act of writing affects reading processes at both cognitive and neural levels in alphabetic systems (James & Gauthier, 2009; James, 2010), and could be even more important for literacy development in Chinese (Lin et al., 2010), which requires the development of precise visual-orthographic representations. Writing characters involves the coupling of visual and motor systems, which may help establish the

spatial configuration of strokes and radicals as well as a temporal sequence of motor movements.

In contrast to the skilled reader's fluent access to the connections among constituents, the adult Chinese as a Foreign Language student acquires constituents at an unequal pace. For this group of Chinese L2 learners, when spoken language is not emphasized in instruction, their orthographic–semantic connections are functional well before their orthographic–phonological connections (Liu, Wang, & Perfetti, 2007), and their visual-orthographic path becomes crucial in learning of a logographic Chinese (Cao et al., 2013a). A high quality orthographic representation is critical for either pathway and writing appears to be helpful in acquiring this representation.

Associations between reading and writing

In English, although research and pedagogy have viewed reading and writing as separate domains (Shanahan, 2006), when studies examined both reading and writing the results suggest that reading and writing are closely related. On a more comprehensive level of reading (including both word reading and text comprehension) and writing (including both handwriting and written composition), there have been a number of research studies on the writing–reading, reading–writing relationship and interaction in the English language (e.g., Berninger, Abbott, Abbott, Graham, & Richards, 2002; Fitzgerald & Shanahan, 2000; Graham, 2006; Shanahan & Lomax, 1986). Correlational analyses of measures of reading and writing indicate that approximately 50 % of their variance is shared. When multiple indicators are available and latent variables can be used to reduce the influence of measurement error, up to 65 % of the variance in reading and writing appears to be shared (Berninger et al., 2002; Shanahan, 2006).

The ability of the character form to drive this character identification process depends on the quality of its representation and its connections to meaning and phonology. Writing may especially strengthen the link from orthography to meaning in word learning. Nevertheless, the research on reading and writing association in Chinese is not as systematic and extensive as that in English. Some researchers studied reading-to-writing relationship (Leong, Loh, Ki, & Tse, 2011; Lin et al., 2010; Qu, Damian, Zhang, & Zhu, 2011), whereas others studied writing-to-reading relationship (Chan, Ho, Tsang, Lee, & Chung, 2006; Guan et al., 2011, Guan, Ye, Wagner, & Meng, 2012, Guan, Ye, Meng, & Leong, 2013, Guan, Ye, Wagner, Leong, & Meng, 2014 McBride-Chang et al., 2011; Tan, Spinks, Eden, Perfetti, & Siok, 2005).

More recent empirical studies of native Chinese speakers have implicated a link between character writing and character reading in terms of word recognition. For example, Tan et al. (2005) found a correlation between native Chinese children's ability to copy characters and their later ability to recognize characters. More direct evidence for a role of writing in recognition comes from priming studies for Chinese characters (Flores d'Arcais, 1994) and in letter perception (Parkinson, Dyson, & Khurana, 2010) among native Chinese adults. Both studies showed that stroke

fragments could prime characters in which they occurred when they were shown in the order in which they were written. This effect implies that information about written stroke order is part of the mental representation of a character. Therefore, it is necessary to understand the role of writing on reading in more depth.

Evidence for writing on reading effects

For alphabetic readers, the writing on reading effect is important. Ehri's (2005) consolidation theory attempts to explain how the different aspects of word learning take place and how they become utilized through practice and learning. In her more recent paper, Ehri (2014) discussed her current position on orthographic mapping in unitizing orthographic elements. For example, for sight word learning, writing forms connections between orthographic forms, pronunciations and meanings in memory. Interestingly, recent studies with French prereaders (Longcamp, Zerbato-Poudou, & Velay, 2005) and adults (Longcamp et al., 2008) have found that letters or arbitrary characters learned through typing were subsequently recognized less accurately than letters or characters written by hand.

To interpret the underlying mechanism, on the one hand, the advantage of handwriting may have a sensory-motor source. Writing provides a mental model of the written form that is accompanied by a new neural motor memory (Shadmehr & Holcomb, 1997). As it becomes stabilized, motor memory can last for a very long period of time without any further practice (Shadmehr & Brashers-Krug, 1997). Some studies even show an improvement of performance, without further practice, after consolidation of neural representation (Brashers-Krug, Shadmehr, & Bizzi, 1996).

On the other hand, the advantage of handwriting may also employ the visual-orthographic path. Neuroimaging studies suggest that writing has an effect on the neural substrate of visual-orthographic processing in English letter learning. More activation in the left fusiform gyrus is observed following writing compared with reading only (James & Atwood, 2009). Taken together, writing also can direct attention directly to visual-spatial information, thus enhancing the reading process.

For native Chinese speakers, learning to read occurs in a literacy context that supports strong connections between reading and writing. Chinese children learn character reading alongside character writing in early literacy instruction. They are taught the appropriate stroke sequences for characters, which become motor programs in memory with practice. Once the motor memory has been learned and stabilized, it can last for long periods, and behavioral studies indicate that sensory-motor memory traces, inferable from stroke sequences in partial character primes, facilitate character recognition (Flores d'Arcais, 1994). Writing-reading connections were demonstrated in correlational studies with normal (Tan et al., 2005) and dyslexic (Chan et al., 2006) Chinese children, and functional brain-imaging has shown that judging visual words involves brain areas possibly associated with writing (Siok, Niu, Jin, Perfetti, & Tan, 2008). Taken together, accumulating behavioral and neuroimaging research supports the hypothesis that writing experience contributes to reading skill in Chinese L1 literacy (Tan et al., 2005;

Siok et al., 2008). Henceforth, several recent empirical studies have extended these writing-on-reading effects to Chinese written language in an adult second language-learning context.

Research has shown that this connection is formed during writing practice of Chinese characters in adult second language-learning context. Specifically, Guan et al. (2011) conducted a series of training studies investigating the role of writing in word-specific recognition processes. They first compared the effects of writing versus reading only. The writing condition led to better performance on word recognition and character-meaning links. They then added an alphabetic typing condition, and found typing supported the character-phonology link. They concluded that the mechanism for the writing effect is the refinement of visual-spatial information needed for character recognition. However, the study offered only 1 day of handwriting training, making it difficult to draw strong conclusions about the relationship between handwriting practice and longer term learning issues. Writing might not be a necessary condition for learning to read Chinese in the long run.

It is still unclear, as writing practice increases, how writing is associated with reading and whether the improvement of writing quality could enhance the reading outcomes in the long term. To fill this research void, we conducted the current study. If writing is a necessary condition for reading, there are different possible mechanisms by which it fills this role. First, the writing practice itself might improve reading, in which case higher-quality practice should lead to greater gains in reading. Alternatively, writing practice might provide an opportunity for knowledge of orthography or phonology to be strengthened, in which case assessments of prior knowledge of these constituents should predict reading gains.

In the current study, we enhance the writing practice to five consecutive days. One day of handwriting training is not enough to achieve optimum of learning in learners of Chinese as a foreign language. As reported in Guan et al. (2011), the effect of 1 day of handwriting training on learning was limited, e.g., it produced 45 % of accuracy in meaning, 61 % of accuracy on form recognition, and 22 and 19 % on pinyin (the alphabetic coding) and tone learning. More days of training are warranted. Furthermore, as to how many days is necessary, a recent fMRI study on the similar population (Cao et al., 2013a) suggested handwriting training produced a progressive gain on character form recognition from 60 to almost 90 %, and revealed that writing affects the brain network of reading and that character writing established higher quality representation of the visual-spatial structure of the character and its orthography. But neither 1-day training study (Guan et al., 2011) nor an fMRI study (Cao et al., 2013a) can explore the association between writing quality and reading. Therefore, in this current study, it is necessary to design a five-day's training to test the association between reading and writing in non-native Chinese learning Chinese. We tested the writing practice effect of each training day (i.e., day 2–day 3, day 3–day 4, and day 4–day 5), rather than the direct progress from day 2 to day 5, in order to capture the relationship between the dynamic pattern of improved writing quality during writing practice and the critical period of change on learning gains.

The current study

The current study was designed to test two major hypotheses. First, handwriting practice supports integration of form, pronunciation and meaning of Chinese characters in adult foreign language learning. Second, the improvement in writing quality during training reflects the long-term retention of the orthographic representations of characters in memory. Alternatively, prior knowledge of orthography or phonology could be the main predictors of reading gains during training.

To test the first hypothesis, a writing-to-read group was compared with a typing-to-read group, to establish that it is stroke-by-stroke production of a character that results in form integration. To test the second hypothesis, quality of writing during training was compared with prior knowledge of stroke order and Chinese phonology in terms of their contributions to learning gains. To test the alternative hypothesis, prior knowledge of orthography and phonology were used as first-step regression predictors to investigate their contributions to learning.

Our experiment tested the additional hypothesis that writing supports reading in the context of adult second language learning, where, in contrast to children's L1 Chinese literacy, the role of writing has not been examined. Orthographic representations are unique for each character and thus place a burden on memory for orthographic forms (Perfetti et al., 2005; Taft, Zhu, & Peng, 1999). This burden may be enhanced for adult students, who are acquiring spoken Chinese while learning to read the language. Under such circumstances, writing may support the learning of the unfamiliar orthographic form by linking it to meaning translations in the native language. Indeed, for adult Chinese foreign language students, the meaning of characters is likely to be learned prior to their form, unless spoken language is strongly emphasized during instruction (Wang, Perfetti, & Liu, 2005).

Methods

Participants

Forty-eight beginning Chinese-as-a-foreign-language college students (ages 16–38, with 6 below 20, 40 between 20 to 30, and 2 above 30) participated in a within-participant design experiment totaling 5 h over five consecutive days learning 90 characters designed in writing-to-read, typing-to-read or novel control condition. They had been in China for half a year and they were enrolled in a basic Chinese learning course at the second semester of their stay in China. They were recruited from a university in southern China and represented 14 countries, including the United States, Finland, Korea, Austria, Nigeria, Greece, Canada, Sweden, South Africa, Sri Lanka, Mexico, Slovakia, Bulgaria and Poland. Their native languages were all alphabetic. Their Chinese proficiency level was elementary as none of them had been exposed to any formal Chinese learning before coming to China. At the study outset, 70 % (35) of the participants could read and write pinyin about 100 characters, and 30 % (13) of the participants could read and write pinyin about 150

characters. They were randomly assigned into different training conditions, and they balanced the age and gender differences as well as the language backgrounds and Chinese learning experience across training conditions.

Design

A 2×2 mixed factorial ANOVA (analysis of variance) tested learning condition as a within-participants factor and presentation order as a between-participants factor. Learning condition was a within-participants factor because all participants learned 30 characters in the handwriting condition, 30 characters in the pinyin-typing condition, and another 30 characters as novel controls (presented in the pretest and posttest, but not taught during the training). Two presentation orders were implemented: reading \rightarrow handwriting and handwriting \rightarrow reading. Half of the participants received the first presentation order, and the other half received the second presentation order. The selection of participants to each presentation order was random. First, the preliminary ANOVA analyses showed no order effect ($ps > .05$), so its effect was not reported or discussed in the ANOVA results revealing the effect of conditions. Second, to test the contribution of improved writing quality for character learning in pronunciation, meaning and form, the 48 subjects' data were submitted for hierarchical regression analyses.

Materials and procedures

Character selection

Ninety characters were selected from Lessons 21–40 in *Chinese Basics II* (Chen & Shen, 2004). Radicals from these lessons had not yet been introduced in class. All were compound characters and three configuration types were represented (top–down, left–right, outside–inside). These characters were divided into three groups matched by configuration type, number of strokes, number of radicals, and English–translation frequency (Kučera & Francis, 1967). One out of each matched set was randomly selected for each of three training conditions: writing-to-read, typing-to-read, and novel control. There were no homophones in the experiment.

Procedures

A pilot study produced the following trial parameters: Up to three times during each 60-s learning trial a character was visually presented for 4 s, followed by 15 s for writing or typing practice (the remaining 3 s allowed transitions from writing/typing to viewing). The 4-s display began with the presentation of the character, viewable the entire 4 s; an audio file of the character's pronunciation began 1 s after display onset; and the English translation of the character appeared for 1 s following pronunciation offset. These parameters were identical for the writing-to-read and typing-to-read conditions. The participants were all tested individually by trained testers on computers onto which the training data and all assessment data were saved for later analyses.

The two learning conditions differed only in the activity completed during the 15-s practice interval. In the writing-to-read condition, participants were told to write the character from memory three times or until time expired. In the typing-to-read condition, they were told to type the character's pinyin and tone three times, or until time expired. After each writing/typing period, the student could reinitiate the 4-s display twice, for a total of three exposures. Thus, the trial time for each character was 60 s, including up to three exposures and 45 s study time, regardless of learning condition. The program then advanced to the next trial. Participants in both learning conditions were encouraged to associate the form of each character with its pronunciation and meaning.

Instrumentation

The tutor was linked to a file server that contained audio files of the characters' pronunciations and image files of characters' forms and English translations. The learning interfaces were designed with Authorware-aligned C language (Fig. 1a, b); the tasks were designed in E-Prime 2.0.

Before training, participants' orthographic and phonological knowledge was assessed through stroke awareness, radical identification, and phonological recognition tasks. We also assessed constituent knowledge through translation and pronunciation tasks at pretest and posttest. A lexical decision task was used to test orthographic, phonological and meaning recognition abilities at each day's training. A detailed description of the implementation of each of these tests is given below.

Tests of prior knowledge

We conducted paper-and-pencil orthographic and phonological tasks prior to the first day's training. To assess stroke awareness, participants were shown 20 unfamiliar characters and were asked to reproduce each character one stroke at a time in what they perceived to be the appropriate order. The maximum score (20) was earned by writing all 20 characters using the correct stroke order. To assess radical knowledge, participants were shown a novel character in the first screen, and were asked to identify the constituent radicals that could make up that novel character out of a group of radicals in the second screen while the original novel character was still on display. For example, presenting a novel character “晴”. The participants were asked to select the appropriate constituent radicals “日” and “青” out of a bunch of radicals including four semantic radicals “日”, “口”, “目”, “月”, and four phonetic radicals “青”, “青”, “亲” and “庆”. The maximum score (20) was earned by correctly identifying all radicals. The composite scores of the radical knowledge and stroke awareness were combined to produce the orthographic awareness score (maximum 40 points), which was later submitted as the control variable in the first step of regression analysis predicting learning from the improved writing quality.

To assess phonological knowledge (or pinyin knowledge), participants heard another 20 novel characters pronounced and were asked to write the pinyin form and



Fig. 1 Interfaces of two learning conditions. **a** Character-writing condition interface. **b** Alphabetic-code typing condition interface

tone (1, 2, 3 or 4) of each character. The maximum score (60) was earned by producing the correct pinyin onset, rime, and tone for each of 20 characters.

Pretest

Although experimental characters were selected to be beyond the students' curriculum range, we assessed students' knowledge of them prior to training. Participants were asked to write the pinyin, tone and English meaning of all 30 characters to be taught in the writing-to-read and all 30 characters to be taught in the

Table 1 Descriptive statistics of knowledge of pinyin, tone and English meaning in pre and posttests during training

Condition	Before training	Day 1	Day 2	Day 3	Day 4	Day 5
<i>Pinyin (%)</i>						
Writing	.33 (.08)	.65 (.11)	.77 (.08)	.85 (.12)	.85 (.06)	.86 (.09)
Typing	.31 (.08)	.57 (.09)	.71 (.07)	.68 (.09)	.73 (.11)	.76 (.09)
Novel	.30 (.10)	.41 (.15)	.52 (.06)	.53 (.07)	.61 (.04)	.61 (.09)
<i>Tone (%)</i>						
Writing	.32 (.08)	.67 (.11)	.75 (.08)	.83 (.12)	.86 (.06)	.87 (.09)
Typing	.31 (.09)	.67 (.09)	.77 (.07)	.78 (.09)	.83 (.11)	.86 (.09)
Novel	.30 (.10)	.41 (.15)	.51 (.06)	.52 (.07)	.57 (.04)	.62 (.09)
<i>English meaning (%)</i>						
Pinyin	.32 (.08)	.57 (.09)	.71 (.07)	.68 (.09)	.73 (.11)	.76 (.09)
Typing	.31 (.10)	.41 (.15)	.52 (.06)	.53 (.07)	.61 (.04)	.61 (.09)
Novel	.28 (.07)	.38 (.07)	.39 (.11)	.41 (.07)	.42 (.06)	.48 (.09)

typing-to-read condition. The 30 characters in the novel control condition were not assessed in the pretest.

Posttest

Following training, participants retook the pretest. Accuracy rates for pinyin, tone and English meaning of all characters taught in either condition over the 5 days of training are given in Table 1.

Lexical decision task

This was our primary recognition test, chosen for its sensitivity to accurate visual-orthographic representations of characters. Participants were given 1,500 ms to decide whether the stimulus was a real character (the task included 120 real and 120 non-characters). The real characters included 60 characters taught in the two learning conditions, the other 30 novel control characters and 30 familiar characters selected from the curriculum (Chen & Shen, 2004). The 120 non-characters included two groups: legal radicals in illegal positions and illegal radicals constructed by adding, deleting or moving a stroke from one location to another within a legal radical. The coefficients of the internal consistency of this measure for 5 days tests are .78, .81, .83, .74, and .81 (Table 2).

Character meaning matching task

This task was used to assess knowledge of character meanings. A Chinese character and an English word were each presented visually for 2,000 ms, separated by a 500-ms ISI. Participants were instructed to hit one key if the English word was a translation of the character and another key if it was not. Stimuli included all 90

Table 2 Descriptive statistics of behavioral tasks performance

Tasks	Condition	During training				
		Day 1	Day 2	Day 3	Day 4	Day 5
Lexical decision (accuracy rate %)	Writing	.66 (.09)	.78 (.08)	.80 (.11)	.87 (.07)	.96 (.06)
	Typing	.55 (.07)	.71 (.07)	.67 (.10)	.72 (.10)	.73 (.10)
	Novel	.42 (.15)	.51 (.07)	.53 (.08)	.61 (.05)	.59 (.09)
Meaning matching (accuracy %)	Writing	.63 (.08)	.73 (.08)	.79 (.10)	.87 (.09)	.96 (.13)
	Typing	.55 (.09)	.56 (.09)	.57 (.09)	.69 (.09)	.77 (.09)
	Novel	.42 (.15)	.51 (.09)	.51 (.10)	.53 (.09)	.55 (.09)
Sound matching (accuracy %)	Writing	.53 (.13)	.54 (.16)	.65 (.12)	.72 (.16)	.85 (.12)
	Typing	.68 (.12)	.78 (.15)	.83 (.12)	.89 (.15)	.97 (.12)
	Novel	.41 (.11)	.49 (.16)	.52 (.09)	.55 (.08)	.57 (.07)

training characters. Half were followed by a matched English meaning and half by a mismatched English meaning. The coefficients of the internal consistency of this measure for 5 days tests are .77, .80, .77, .78, and .78.

Character sound matching task

This task required participants to decide whether a visually presented Chinese character matched an auditorily presented pronunciation. Characters for whom pronunciations were familiar were expected to have shorter response times and higher accuracy rates than those whose pronunciations were unfamiliar. The task included all 90 characters (30 in handwriting-to-read condition, 30 in typing-to-read condition, 30 as novel control). Half were followed by a matched pronunciation and half by a mismatched pronunciation. The coefficients of the internal consistency of this measure for 5 days tests are .74, .75, .75, .76, and .77.

Writing quality

Quality of participants' writing was judged according to the four criteria of a coding schema (detailed below) that took into account both local and global stroke conformity. The coding schema was designed on an exploratory basis to consider both character formation principles and Chinese handwriting habits. Inclusion of the two levels was based on Zhu and Taft's (1994) seminal work on Chinese character processing, and follows their speculation that skill moves from the component level to the whole character level. Follow-up studies in Chinese orthography processing support this conceptualization. In addition, it has been shown that mastership in Chinese handwriting progresses first from the individual stroke, to the radical, and finally to the whole character (Qiu, 2000; Wu et al., 1999). Each character has strict rules of stroke and geometric order, including shape and configuration. Therefore, we categorized the stroke and radical on the local level, and the shape and configuration on the global level.

Chinese character coding schema

I. Local conformity

I-A. Basic stroke form correctness (cf. Fei, Huang, & Zhang, 1992; Wang & Xu, 1993; Wen, 1964)

There are eight basic stroke forms (Fig. 2). The first author and a graduate student separately calculated the percentage of individual strokes in the character produced incorrectly, and awarded the character 1 minus that percentage. For example, a five-stroke character in which one stroke had an incorrect form was coded as .8. The appropriated size of each stroke and their compactness are considered in the coding schema. The inter-rater reliability used coefficients of the internal consistency of this coding measure on two raters for 5 days tests are .75, .76, .74, .71, and .74.

I-B. Radical correctness

Regardless of the correctness of the strokes, they should combine to make a correct radical. If all the radicals in a character were complete, the character was coded as 1; the character was coded as .5 if any radical within the character contained extra or missing strokes; and the character was coded as 0 if all radicals in the character were incorrect, or if any radical was absent. The appropriate size of each radical and their compactness are considered in the coding schema. The coefficients of the internal consistency of this coding measure on two raters for 5 days tests are .74, .75, .76, .77, and .74.

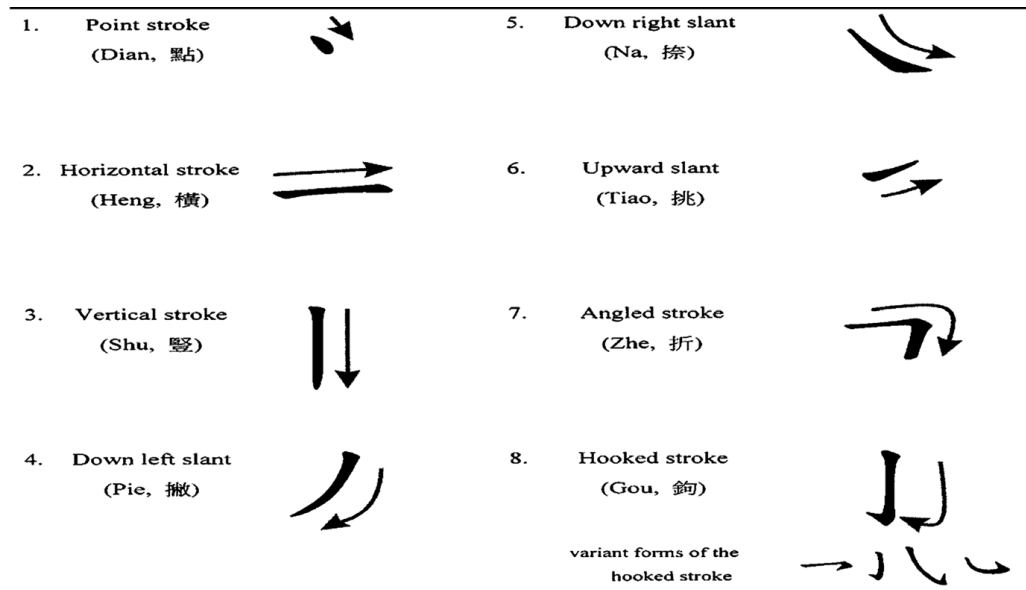


Fig. 2 Eight basic strokes of Chinese character writing

II. Global conformity

II-A. Conformity to the conventional shape

Chinese characters offer no flexibility in the shape they take; all must conform to a squared configuration. 1 = Squared shape for the whole character; 2/3 = Unified shape for each of the two radicals but no squared conformity; 1/3 = Unified shape for each of the components, but no radical or squared conformity; 0 = Flawed squared shape OR any other unconventional shape OR nothing. The coefficients of the internal consistency of this coding measure on two raters for 5 days tests are .84, .85, .86, .89, and .85.

II-B. Conformity to the proper configuration

The possible relationships between the components of characters are left–right, top–bottom, and outside–inside. A character was coded as 1 on this criterion if the component relationship was correct, and 0 if the component relationship was incorrect. The coefficients of the internal consistency of this coding measure on two raters for 5 days tests are .73, .75, .74, .75, and .77.

Training and testing schedule

The experiment was carried out on 5 separate days. The assessments of prior orthographic and phonological knowledge and the pretest of knowledge of pinyin, tone and English meaning were administered immediately before Day 1's training, and the posttest was administered immediately after each day's training. The lexical decision task, character meaning matching task, and character sound matching task were all administered after the posttest at the end of each day.

Research questions and analyses

To answer the first research question—Is there a practice effect of character writing and/or pinyin typing on Chinese word learning across five training days?—we carried out factorial analyses of lexical constituent knowledge (assessed by lexical decision, meaning matching, and sound matching tasks) controlling for prior knowledge (assessed by orthographic and phonological knowledge tasks). Repeated measures ANOVAs were run on these three behavioral measures, with training day and treatment condition as within-participant factors, and prior knowledge scores as covariates. Because the participants were Chinese L2 learners rather than skilled readers of Chinese, accuracy rather than response time was the dependent variable on the three behavioral tasks assessing form, pronunciation and meaning recognition. Accuracy is a more appropriate indicator than speed for second language beginners (Ellis, 1997; Krashen, 1981), and the level of accuracy is the representation of memory in language processing (Foraker & McElree, 2011).

To answer the second research question—Does the improvement in the quality of character writing or pinyin typing during training predict character learning gains better than prior knowledge of orthography and phonology?—we used hierarchical regression (HR) analyses on lexical knowledge (i.e., form, pronunciation and meaning) learning gains (i.e., the proportional change scores of the lexical constituent knowledge of form, pronunciation and meaning across days). To evaluate the practice effect on Chinese learning gains, the students' writing quality was assessed on four categories: stroke form correctness, radical form correctness, shape conformity and configuration conformity. Typing quality was assessed on two categories: pinyin correctness and tone accuracy. The prior knowledge scores (for orthographic and phonological knowledge) were entered into the model first, followed by the practice variables (quality of writing or typing on each day of training). Both the radical and stroke awareness measures were used as indicators of orthographic knowledge. Proportional change scores for form, pronunciation and meaning of all 30 characters taught in either of writing-to-read or typing-to-read condition served as the three dependent measures. Two treatment conditions on five treatment days resulted in ten separate HR analyses (see Tables 3, 4, 5, 6, 7, 8, 9, 10).

As hierarchical regression does not tell which predictors are more important, and our exploration is to examine the relative importance between the local-level and global-level writing quality to reading, we used the switching-order approach to arrange the order of three sets of variables (i.e., prior knowledge of either orthography or phonological knowledge, the local conformity and the global conformity) for each regression model. The switch-order approach was used to arrange the variables (see Table 11 for details). We always inserted prior knowledge in block 1, as we wanted to control for the prior knowledge of orthography for handwriting and phonology for pinyin-typing. For the other two blocks, we combined prior knowledge with either local or global conformity. Specifically, for order 1, we entered prior knowledge in block 1, prior knowledge and two variables of local conformity in block 2, prior knowledge, two variables of local conformity and two variables of global conformity in block 3. For order 2, we entered prior knowledge in block 1, prior knowledge and two variables of global conformity in block 2, prior knowledge, two variables of global conformity and two variables on local conformity in block 3). Similarly, for the characters taught in the typing-to-read condition, the practice effects of pinyin and tone correctness were entered into the model as block 2 after controlling for the phonological knowledge prior knowledge score in block 1.

Three separate dependent measures were used for the five training days in the HR analyses: (1) the lexical decision task form recognition gain scores from Day 2 to Day 5; (2) the sound posttest gain scores from Day 2 to Day 5, and (3) the English meaning posttest gain scores from Day 2 to Day 5 (Day 1 performance served as the baseline score).

The R-square change of each block in the HR analyses were presented in Table 11, from which we can see that there is a systematic and consistent result pattern of R-square change. The R-square change of local conformity (global-conformity) remains almost the same when entering before or after global conformity (local conformity). For outcome variables Form and Meaning, the local

Table 3 HR analyses explaining word learning gains on *Day 2* from orthography knowledge and writing quality-related gain scores from *Day 1* to *Day 2*

Step	Variables	LexicalDecisionGainDay 2-1			PinyinToneGainDay 2-1			MeaningGainDay 2-1								
		B	SE(B)	β	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2
1	Orthography knowledge	.004	.001	.443	.20	.20**	.003	.003	.176	.03	.03	.003	.001	.357	.12	.12*
2	GrowthStroke2-1	.124	.056	.231	.30	.10**	-.020	.167	-.022	.06	.03	.336	.167	.334	.23	.11*
	GrowthRadical2-1	.343	.135	.291			-.440	.503	-.179			.530	.263	.313		
3	GrowthShape2-1	.007	.079	.010	.33	.03	.020	.259	.015	.06	.00	-.80	.161	-.087	.24	.01
	GrowthConfiguration2-1	-.055	.105	-.061			.080	.331	.048			.050	.197	.043		

N = 48

* $p < .05$; ** $p < .01$

Table 4 HR analyses explaining word learning gains on *Day 3* from orthography knowledge and writing quality-related gain scores from *Day 2* to *Day 3*

Step	Variables	LexicalDecisionGainDay 3–2				PinyinToneGainDay 3–2				MeaningGainDay 3–2				
		B	SE(B)	β	R ²	B	SE(B)	β	R ²	B	SE(B)	β	R ²	ΔR^2
1	Orthography knowledge	-.001	.003	-.076	.01	.003	.003	.158	.03	.003	.002	.238	.06	.06
2	GrowthStroke3–2	.414	.100	.519	.09	-.236	.212	-.296	.06	.318	.274	.367	.21	.15**
	GrowthRadical3–2	.458	.131	.439		.091	.279	.087		.202	.336	.191		
3	GrowthShape3–2	-.021	.142	-.013	.10	-.299	.291	-.192	.07	-.300	.254	-.186	.25	.04
	GrowthConfiguration3–2	.004	.255	.002		-.702	.521	-.282		.168	.415	.065		

N = 48

* $p < .05$; ** $p < .01$

Table 5 HR analyses explaining word learning gains on *Day 4* from orthography knowledge and writing quality-related gain scores from *Day 3* to *Day 4*

Step	Variables	LexicalDecisionGainDay 4-3				PinyinToneGainDay 4-3				MeaningGainDay 4-3						
		B	SE(B)	β	R^2	ΔR^2	B	SE(B)	β	R^2	ΔR^2	B	SE(B)	β	R^2	ΔR^2
1	Orthography knowledge	.000	.003	-.030	.00	.00	-.003	.002	-.200	.04	.04	.003	.001	.320	.10	.10
2	GrowthStroke4-3	-.275	.304	-.171	.03	.03	-.229	.199	-.202	.16	.12	-.223	.207	-.185	.15	.05
	GrowthRadical4-3	-.062	.249	-.046			.257	.163	.273			.122	.180	.122		
3	GrowthShape4-3	.734	.266	.465	.20	.17**	.010	.268	.009	.18	.02	.215	.224	.190	.35	.20
	GrowthConfiguration4-3	.865	.295	.468			.221	.297	.170			.578	.236	.467		

N = 48

* $p < .05$; ** $p < .01$

Table 6 HR analyses explaining word learning gains on *Day 5* from orthography knowledge and writing quality-related gain scores from *Day 4* to *Day 5*

Step	Variables	LexicalDecisionGainDay 5-4				PinyinToneGainDay 5-4				MeaningGainDay 5-4						
		B	SE(B)	β	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2
1	Orthography knowledge	-.001	.001	-.238	.06	.06	-.001	.002	-.101	.01	.01	.004	.001	.437	.19	.19*
2	GrowthStroke5-4	-.067	.108	-.113	.10	.04	-.079	.259	-.055	.09	.08	.182	.258	.117	.23	.04
	GrowthRadical5-4	.140	.139	.184			.532	.333	.292			.357	.338	.179		
3	GrowthShape5-4	.235	.103	.290	.20	.16**	.130	.475	.067	.10	.01	1.059	.417	.518	.40	.17*
	GrowthConfiguration5-4	.702	.131	1.056			.118	.603	.074			.144	.335	.093		

N = 48

* $p < .05$; ** $p < .01$

Table 7 HR analyses explaining word learning gains on *Day 2* from phonological knowledge and typing quality-related gain scores from *Day 1* to *Day 2*

Step	Variables	LexicalDecisionGainDay 2-1			PinyinToneGainDay 2-1			MeaningGainDay 2-1										
		B	SE(B)	β	R ²	ΔR^2	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2					
1	Phonological measure	.947	.386	.444	.03	.03	.334	.195	.301	.18	.18	.18	.18**	.004	.002	.340	.04	.04
2	PinyinCorrectness2-1	.003	.002	.222	.07	.04	.001	.001	.189	.28	.10	.28	.10	-.947	.386	-.444	.11	.07
	ToneAccuracy2-1	.043	.468	.027			.099	.128	.140					.043	.368	.017		

N = 48

* $p < .05$; ** $p < .01$

Table 8 HR analyses explaining word learning gains on *Day 3* from phonological knowledge and typing quality-related gain scores from *Day 2* to *Day 3*

Step	Variables	LexicalDecisionGain 3–2			PinyinToneGainDay 3–2			MeaningGainDay 3–2								
		B	SE(B)	β	R ²	ΔR^2	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2			
1	Phonological measure	.006	.003	.359	.03	.03	.558	.211	.481	.12	.12**	.414	.150	.202	.10	.10
2	PinyinCorrectness3–2	.094	.586	.029	.08	.05	.008	.089	.016	.20	.08	-.370	.432	-.160	.20	.10
	ToneAccuracy3–2	.161	.873	.130			.005	.001	.011			-.326	.476	-.130		

N = 48

* $p < .05$; ** $p < .01$

Table 9 HR analyses explaining word learning gains on *Day 4* from phonological knowledge and typing quality-related gain scores from *Day 3* to *Day 4*

Step	Variables	LexicalDecisionGain 4-3			PinyinToneGainDay 4-3			MeaningGainDay 4-3								
		B	SE(B)	β	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2					
1	Phonological measure	1.171	.544	.378	.04	.04	.002	.001	.348	.12	.12**	1.042	.391	.489	.07	.07
2	PinyinCorrectness4-3	-.674	.453	-.297	.09	.05	.285	.200	.242	.18	.06	.000	.002	.039	.10	.03
	ToneAccuracy4-3	-.107	.474	-.043			-.026	.089	-.051			.073	.492	.028		

N = 48

* $p < .05$; ** $p < .01$

Table 10 HR analyses explaining word learning gains on *Day 5* from phonological knowledge and typing quality-related gain scores from *Day 4* to *Day 5*

Step	Variables	LexicalDecisionGain 5-4			PinyinToneGainDay 5-4			MeaningGainDay 5-4								
		B	SE(B)	β	R ²	ΔR^2	B	SE(B)	β	R ²	ΔR^2					
1	Phonological measure	.004	.002	.340	.04	.04	.405	.154	.429	.18	.18*	.006	.003	.359	.03	.03
2	PinyinCorrectness5-4	.947	.386	.443	.11	.07	-.057	.091	-.105	.26	.08	.094	.586	.029	.14	.11*
	ToneAccuracy5-4	.043	.468	.017			.000	.001	-.156			1.717	.544	.378		

N = 48

* $p < .05$; ** $p < .01$

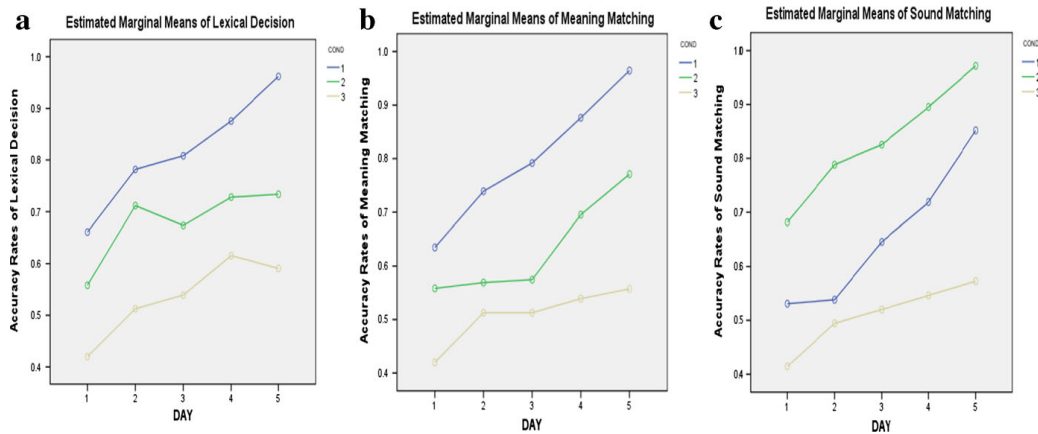


Fig. 3 Accuracy rates across days for the three conditions for lexical decision, meaning matching and sound matching performance. 1 writing to read condition, 2 typing to read condition, 3 novel control condition

conformity shows higher and significant R-square change for days 2 and 3, while the global conformity shows higher and significant R-square change for days 4 and 5. Neither the local nor the global conformity presents significant R-square change for pronunciation learning.

Results

Writing versus typing practice effects on lexical constituent representations

Three (conditions) by five (days) repeated measures ANOVA indicated a consistent effect of writing practice on form, pronunciation, and meaning, but a typing practice on pronunciation only (see Table 2). Details are given below and are graphed in Fig. 3.

Practice effects on orthographic representations

There were significant main effects of condition [$F(2,62) = 35.81$, $MSE = .245$, $p < .001$, $\eta_p^2 = .54$] and day [$F(4,124) = 3.78$, $MSE = .023$, $p = .006$, $\eta_p^2 = .11$], and condition-by-day interaction [$F(8,248) = 7.39$, $MSE = .025$, $p < .001$, $\eta_p^2 = .19$]. Mean lexical decision accuracy rates for all three conditions improved steadily across days (54.6, 66.9, 67.4, 74.0 and 76.2 % on Day 1 to 5). The improvement within the writing-to-read condition was significant for each progressive phase, with 66.9, 78.2, 80.8, 87.45, and 96.2 % from Day 1 to 5 ($ps < .05$).

The improvement within the typing-to-read condition was significant only from Day 1 (55.8 %) to Day 2 (71.2 %), and from Day 3 (67.4 %) to Day 4 (72.8 %) ($ps < .001$). Averaging across days, the lexical decision accuracy rate for characters

Table 11 R-square changes of each block for the predictors using switch-order approach explaining writing quality related gain scores

Days	Block	Sets of variables	Form	Pronunciation	Meaning	Sets of variables	Form	Pronunciation	Meaning
From Day2 to Day1	1	Prior knowledge	.20**	.03	.12*	Prior knowledge	.20**	.03	.12*
	2	Local conformity	.10**	.03	.11*	Global conformity	.04	.02	.02
	3	Global conformity	.03	.00	.01	Local conformity	.11**	.01	.11*
From Day3 to Day2	1	Prior knowledge	.01	.03	.06	Prior knowledge	.01	.03	.06
	2	Local conformity	.08**	.03	.15**	Global conformity	.03	.02	.05
	3	Global conformity	.01	.01	.04	Local conformity	.07**	.02	.15**
From Day4 to Day3	1	Prior knowledge	.00	.04	.10**	Prior knowledge	.00	.04	.10**
	2	Local conformity	.03	.12	.05	Global conformity	.17**	.06	.21**
	3	Global conformity	.17**	.02	.20**	Local conformity	.03	.06	.04
From Day5 to Day4	1	Prior knowledge	.06	.01	.19*	Prior knowledge	.06	.01	.19*
	2	Local conformity	.04	.08	.04	Global conformity	.16**	.04	.17*
	3	Global conformity	.16**	.01	.17*	Local conformity	.04	.04	.04

Local conformity refers to the two variables showing the growth values of stroke and radical correctness from 1 day to the succeeding day, global conformity refers to the two variables showing the growth values of conventional shape and configuration from 1 day to the succeeding day

N = 48

* $p < .05$; ** $p < .01$

learned in the writing-to-read condition (81.8 %) was significantly better than that in the other two conditions (68.1 % for typing and 53.6 % for novel) (see Fig. 3a).

Practice effects on semantic representations

Accuracy rates for the meaning matching task improved from Day 1 to Day 5 for the writing-to-read condition only. There were significant main effects of condition [$F(2,62) = 52.67$, $MSE = .313$, $p < .001$, $\eta_p^2 = .63$] and day [$F(4,124) = 6.60$, $MSE = .025$, $p < .001$, $\eta_p^2 = .18$], and condition-by-day interaction [$F(8,248) = 7.16$, $MSE = .017$, $p < .001$, $\eta_p^2 = .19$]. Mean matching accuracy rates improved across days (53.6, 59.9, 62.4, 69.0 and 76.2 % from Day 1 to 5). The improvement within the writing-to-read condition was significant for each progressive phase, with 63.5, 73.9, 79.82, 87.6 and 96.5 % from Day 1 to 5 ($ps < .05$).

The improvement within the typing-to-read condition was significant from Day 3 (57.5 %) to Day 4 (69.5 %), and Day 4 to Day 5 (77.1 %) ($ps < .001$). Averaging across days, the meaning matching accuracy rates for characters learned in the writing-to-read condition (80.1 %) was significantly better than that in other two conditions (63.4 % for typing and 50.8 % for novel) (see Fig. 3b).

Practice effects on phonological representations

Unlike the previous two tasks, the sound matching task showed an advantage for the typing-to-read condition over the writing-to-read condition. Accuracy rates for the typing-to-read condition improved consistently from Day 1 to Day 5, whereas accuracy rates for the writing-to-read condition did not show significant growth until Day 3. ANOVAs revealed significant main effects of condition [$F(2,62) = 20.23$, $MSE = .149$, $p < .001$, $\eta_p^2 = .40$], day [$F(4,124) = 4.60$, $MSE = .011$, $p = .002$, $\eta_p^2 = .13$], and condition-by-day interaction [$F(8,248) = 14.73$, $MSE = .041$, $p < .001$, $\eta_p^2 = .32$]. Mean sound matching accuracy rates improved steadily across the five learning phases (54.2, 60.7, 66.4, 72.0, and 79.9 % from Day 1 to 5). The improvement within the typing-to-read condition was significant for each progressive day (68.2, 78.8, 82.6, 89.6, and 97.2 % from Day 1 to 5) ($ps < .05$).

Reversing the pattern from the previous tasks, the improvement within the writing-to-read condition was significant from Day 2 (53.8 %) to Day 3 (64.6 %), Day 3 to Day 4 (71.9 %), and Day 4 to Day 5 (85.2 %) ($ps < .001$). Averaging across days, the sound matching accuracy rates for characters learned in the typing-to-read condition (83.3 %) was significantly better than that in the other two conditions (65.7 % for writing and 51.0 % for novel) (see Fig. 3c).

Practice and prior knowledge effects on word and pronunciation learning

HR analyses revealed the unique contribution of either prior knowledge or practice effect on learning the form, pronunciation, and meaning. Prior knowledge was

indexed by pre-training performance on orthography and phonology assessments in both conditions. The practice effect was indexed by daily gain scores (e.g., Day 2–Day 1) of performance on writing or typing quality.

According to Table 2, performance generally improved across days for all conditions. The goal of the next set of analyses was to examine whether writing quality or prior knowledge predicted learning of character form, pronunciation and meaning. According to Tables 3 and 4 for writing-to-read condition, and Tables 7 and 8 for the typing-to-read condition, the results suggest a writing practice effect on character learning, with local writing quality predicting learning in early treatment, and global writing quality predicting learning in later treatment. Typing practice did not contribute to learning of character form or meaning, but the pre-training phonological knowledge measure predicted character pronunciation learning through treatment overall.

Writing practice quality predicts word learning

Writing quality at the local level predicted early Chinese word learning, and writing quality at global levels predicted Chinese word learning at later stages. HR analyses of the lexical decision gain scores revealed the two local writing quality variables significantly explained an additional 10 and 8 % ($ps < .01$) of variance in lexical decision gain scores on Day 2 and 3 (Tables 3, 4). By contrast, the two global writing quality variables significantly explained 17 and 16 % ($ps < .01$) of variance in lexical decision gain scores on Day 4 and 5 (Tables 5, 6).

HR analyses of the English meaning posttest gain scores show that the two local writing quality variables significantly explained an additional 11 and 15 % ($ps < .05$) of variance in meaning matching gain scores on Day 2 and 3 (Tables 3, 4). Conversely, the two global writing quality variables significantly explained 20 and 17 % ($ps < .05$) of variance in meaning posttest gain scores on Day 4 and 5 (Tables 5, 6).

Finally, the HR analyses of the pinyin and tone posttest gain scores revealed neither local nor global writing quality variables predicted posttest gain scores on pronunciation learning across days (Tables 3, 4, 5, 6).

Prior knowledge of phonology predicts pronunciation learning

Typing quality did not contribute to character learning, whereas pre-training knowledge on the phonological knowledge task significantly predicted pinyin and tone posttest gain scores on Day 2–5, explaining 18, 12, 12 and 18 % ($ps < .05$) of variance in pinyin and tone performance gains (see Tables 7, 8, 9, 10).

Discussion

The current study demonstrates that the character writing quality of Chinese L2 learners is associated with the character reading outcomes on phonology, form and

meaning after 5 day's manual writing training. By contrast, pinyin-typing training produced effects limited to pronunciation. The study shows specific effects of character practice, with incremental gains in writing quality over 5 days that occur at both the component level and the global level of character formation. This distinction between global and component (or local) levels is in the spirit of Zhu and Taft's (1994) speculation that skill in Chinese character processing moves from the stroke level to the whole character level. In our study, the component or local level quality was dominant in the early practice gains in writing quality, with global-level quality showing a later emergence. Finally, the results further suggest that for L2 adult learners, writing primarily strengthens the association between orthography and semantics, replicating the result of Guan et al. (2011).

The writing practice effect

The first major finding confirms that the effects of writing practice on reading can occur with relatively modest writing opportunity. The adult learners of Chinese visually recognized characters more consistently and associated their forms with meanings more accurately in the writing condition than in the typing condition. Furthermore, instruction through character-writing produced better recognition performance than did instruction through typing. Characters taught in the character-writing condition were judged more accurately than those taught in the typing condition.

To the best of our knowledge, this study is the first to directly assess the role of repeated writing practice in orthographic recognition in adult Chinese L2 beginners. Although a more specific explanation requires further research, the current study shows that handwriting (a) increases the quality of the orthographic form and (b) selectively strengthens the connection from orthography to meaning (but not from orthography to phonology) for the population of adult Chinese learners. These findings are supported by a recent fMRI study (Cao et al., 2013a), in which left temporal lobe areas associated with meaning processing, as well as visual-spatial and motor areas, were activated during character reading for characters that had been learned with writing. Together, the studies suggest that meaning-focused learners can use their knowledge of Chinese orthography to complete the orthography-semantics association link. The orthography-phonology connection might be strengthened as spoken language skills improve.

The current study along with Guan et al. (2011) and Cao et al. (2013a) extends the writing effects from native Chinese children (Tan et al., 2005), native Chinese adults (Flores d'Arcais, 1994; Parkinson et al., 2010), alphabetic readers (Longcamp et al., 2005, 2008) to adult Chinese L2 learners, who must attend to the visual features of the character in association with meaning and pronunciation as the learn characters. Cao et al. (2013a) found that the early stage visual processing supports the acquisition of a visual representation that can support meaning and pronunciation connections in long-term memory. Our results add the possibility that a high quality orthographic representation is needed to support lexical identity in Chinese and in reading more generally.

For both native speakers and second language learners, the advantage of handwriting may have a sensory-motor source (Cao et al., 2013a). Writing characters involves the coupling of writing-related visual and motor systems. This coupling may help establish the spatial configuration of strokes and radicals, which along with a temporal sequence of motor movements associated with stroke composition, completely defines the shape of the character (Wu et al., 1999). Two other studies have also found writing-related motor information is involved in the process of visual recognition (James & Gauthier, 2009; Longcamp et al., 2005). Consequently, writing provides a mental model of the written form that is accompanied by a new neural motor memory. The motor memory is wired with the visual perceptual representation to enhance learning.

Writing quality reflects acquisition of orthographic representations

The second major finding confirms that knowledge of the correct sequence of character strokes predicts the accurate recognition of a character's orthographic form. Furthermore, stroke sequence knowledge and the ability to correctly produce the constituent radicals of a character predict the recognition of a character's orthographic form and meaning after several days' training. First, orthography knowledge (including the stroke and radical awareness) predicted character learning after the first day's writing training. This finding indicates that orthographic learning of Chinese characters is supported by prior knowledge of the basic writing procedures that encode the sequence of strokes. But this prior knowledge explained less than 20 % of the variance in learning at earlier stage. Later, during writing instruction, the acquisition of character representations is associated with the quality of the writing produced, when stroke sequencing and radical positioning are used as indicators of writing quality. This is due to the fact that repeated character writing practice led to high accuracy in reading those characters. Through writing practice, the learners learned the concrete forms of the various logo-graphemes and their positional regularities in these Chinese characters. The key learning event, we suggest, is that writing required the learner to encode the internal structures of characters in order to copy the characters accurately from memory.

This study directly shows the coordinated acquisition of character writing and character recognition in an adult second language character recognition context. This interconnected growth may reflect a unified process of visual memory that is reflected both in recognition memory and in detailed form recall (copying from memory). Studies of native Chinese speakers have previously indicated such a link between handwriting skill and reading acquisition (Tan et al., 2005; McBride-Chang et al., 2011). For example, McBride-Chang et al. (2011) found that skill in handwriting across orthographies is associated with the development of Chinese literacy. Specifically, they found that skill in writing Hebrew, Korean, and Vietnamese graphs from memory explained 6 % of variance in word reading for children learning to read Chinese. These studies establish handwriting skill as an indicator of Chinese reading and dictation abilities and align generally with the findings of alphabetic languages, which suggest that children's handwriting

legibility represents the quality of writing, which is in turn associated with their literacy development (Graham & Hebert, 2011).

Handwriting practice effect progresses from local to global levels

In considering the various aspects of character writing quality, we identified sub-categories at the local component and global levels. This system allowed observations on the emergence of different aspects of writing quality and their predictability for character reading. Repeated writing practice led to gains in local and sub-lexical word processing and these gains, in terms of the correctness of both strokes and radicals, predicted Chinese character learning. Component-level (i.e., strokes and radicals) processing skills play a dominant role in Chinese orthographic learning by facilitating the integration of form and meaning in the preliminary stages of character learning. Recent research on Chinese learners' writing difficulties similarly suggested that component-level processing is fundamental to Chinese word reading, and deficits in this area (e.g., the component-level processing stored in the orthographic buffer) can be detrimental to Chinese dysgraphic patients (Han, Song, & Bi, 2011).

Furthermore, the results of the fourth and fifth day's training revealed the specific role of repeated character writing in developing an integrated more global representation of Chinese characters. After basic, component-level processing skills are acquired, global-level knowledge (in terms of overall shape and configuration) and prior knowledge of orthography emerged as predictors of Chinese learning. This sequence suggests that in learning Chinese characters, basic visual attention processes that build local or sub-character knowledge components provide a foundation for further learning of configurational knowledge. The progression of handwriting effects from local to global levels could be viewed in the context of Verhoeven's (2013) lexical practice effect. On this view, the length of the intervention is responsible for the progression of effects, with higher writing quality during the course of training resulting in higher reading proficiency by the end of training.

Limitations

One limitation of our study lies in the use of behavioral coding rather than systematic rubrics for handwriting quality. We established our coding system according to several classic studies (Fei et al., 1992; Wang & Xu, 1993; Wen, 1964), which failed to examine the reliability and validity of the coding measures. However, we did not take into account stroke order, a crucial element of Chinese writing, when we conducted the regression analysis. We controlled for variance in stroke order knowledge to a certain extent by assessing the participants knowledge of some typical stroke orders of a set of novel control characters. A second limitation is that we did not test the long term effects of writing practice. However, prior studies of adult L2 learners have found effects at 4 weeks after testing (Cao et al., 2013b). A third limitation is the nature of our writing condition. In future exploration, it is necessary to add a pure-writing condition in contrast to a comparable writing condition.

Conclusion

Writing characters as part of learning to read supports character reading. This conclusion is consistent with earlier behavioral (Guan et al., 2011) and neuroimaging (Cao et al., 2013a) research, which found evidence for an effect of writing on reading within comparable populations of L2 adult learners. In the present study, we have shown that the key mechanism for this writing effect is the refinement of visual–spatial information that writing establishes (James, 2010). Character learning includes all three lexical constituents of visual form, meaning, and pronunciation. In adult second language learning, at least without a strong grounding in the spoken language, the connection between visual form and meaning is acquired more readily, with the connection between visual form and pronunciation coming second.,

Although writing may play a larger role in reading Chinese than in alphabetic reading, a reader's writing experience is also functional and important in reading alphabetic writing. Recent research by Nakamura et al. (2012) suggests that reading handwritten French activates a left frontal pre-motor region (Exner's area) that has a role in writing production. This is in accordance with Ehri's consolidation theory, as handwriting is instrumental in consolidating the memories for word form, meaning, and phonological articulation, which was particularly strengthened during the spelling process (Ehri, 2005, 2014).

In adult second language learning, opportunities for repeated writing may be important for reading, especially for less familiar forms. However, recent evidence suggests that for L2 adult learners some familiarity with characters needs to precede writing practice for it to be effective (Chang et al., 2014). The positive effects of practice occur at both the basic level of stroke sequences and at the higher level of radical knowledge, including radical form and position, which often signals character meaning. Instruction relating to these fundamental aspects of character formation has long been central to traditional Chinese literacy instruction.

Overall, the current study establishes a detailed picture of how writing quality improves with practice and how its different aspects predict later character recognition. It joins previous studies in providing implications for L2 classroom instruction and for theories of orthographic learning.

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