Abstract

Visual-motor integration is an ability to coordinate the visual information and limb movement, which has direct relevance to Chinese handwriting ability. Interestingly handwriting practice can also improve Chinese reading. However, the relationship between visual-motor integration and reading ability in Chinese is unclear. The present study investigated the role of visual-motor integration skills in reading Chinese among children with and without developmental dyslexia. In the study Chinese children with developmental dyslexia (DD-Group), chronological-age-matched children (CA-Group), and reading-level-matched children (RL-Group) were asked to participate in reading and reading related tasks as well as word-copying and picture-copying (visual-motor integration) tasks. The results revealed that the DD-Group performed significantly worse than the CA-Group on the word copying task, and that the DD-Group performed similarly to the RL-Group on the reading and reading related tasks and the word-copying task. However, the DD-Group performed significantly worse than the CA- and RL-Groups on the visual-motor integration task. Further, when age and intelligence were controlled visual-motor integration and word-copying skills could explain 14% and 16% of the variance in reading skills respectively. When reading-related cognitive skills were controlled, visual-motor integration skills could still explain 8% of variance in reading skills, but word-copying skills did not. The results of the current study indicated for the first time that visual-motor integration skills play an essential role in reading Chinese independent of word copying ability.

Keywords Chinese developmental dyslexia, reading, word copying, visual-motor integration

Learning to read involves a complex system of relatively broad multiple skills including visual (Kevan & Pammer, 2009), phonological (Ziegler & Goswami, 2005), orthographic (Booth et al., 2002; Price & Devlin, 2011) and semantic processing (Price, Moore, Humphreys, & Wise, 1997). In a prominent theory, children's sensitivity to the phonological structure of words plays a vital role in reading acquisition (Vellutino & Scanlon, 1986). Extensive research lends support to this theory, suggesting that children's phonological processing ability serves as a general mechanism governing reading performance in alphabetic languages (Bradley & Bryant, 1983; Wydell & Butterworth, 1999). Others however showed that other cognitive skills such as orthographic processing, rapid naming and morphological awareness skills are also related to reading development (Booth et al., 2002). Thus, acquisition of lexical orthographic processing skills is essential in word reading (Badian, 1997).

I. Visual-motor integration and Handwriting

It is known that handwriting practice can help the learning of word orthography rather than typing (Longcamp et al, 2005). As individuals engage in handwriting practice, they become faster and proficient to recall and execute the commands to produce legible letter/word form (Medwell & Wray, 2014). This is because handwriting could aid pattern recognition when reading because of more practiced recall of letter/word forms (Waterman, Havelka, Culmer, Hill, & Mon-Williams, 2015).

Some researchers thought that the relationship between reading and handwriting might rely on the motor aspects of handwriting (Longcamp et al., 2005; Longcamp et al., 2016). The skill is learning how to generate motor commands that result in the hand producing a representation of a visual shape (alphabetic symbol). Definition of this psychological process is “visual-motor integration” (VMI) (the coordination and integration between the visual perception and finger–hand movements (Tinker, 1940). Weintraub and Graham (2000) found that in alphabetic languages visual-motor integration skills made a unique and significant contribution to the *handwriting status* of fifth grade elementary school children. Handwriting status (e.g., good vs poor) was determined by the Test of Legible Handwriting (TOLH) (Larsen & Hammill, 1989). Weintraub and Graham asked their participants to write alphabetic letters for 15 minutes, and subsequently each handwritten letter was rated on a scale of 1-9 point, and thus the handwriting status represented the handwriting legibility of participants. Moreover, another study revealed that participants with a difficulty in handwriting had been found to show a visual-motor dysfunction, and thus the study suggests that there appear to be a direct relationship between visual-motor integration and handwriting (Volman, van Schendel, & Jonmans, 2006).

A Chinese character is composed of strokes and radicals that are packed into a square configuration, possessing a high, nonlinear visual complexity (Chow, Choy, & Mui, 2003; Tan et al., 2005). Thus, in order to write Chinese characters legibly it is necessary to visually discriminate differences in structures and positions of strokes first (Huang, 1984), and also necessary to be aware of a high-order organization of strokes and radicals (Tseng, 1993). A perceptual-motor ability, which may result in pairing of hand movement and language stimuli will help form a close association between long-term motor memory of Chinese characters and visual representations of written Chinese. Thus the perceptual-motor ability may facilitate the development of Chinese handwriting skills.

It has been suggested that visual-motor integration skills, as a kind of perceptual-motor ability, is related to Chinese handwriting ability. For example, Tseng and Chow (2000) found that the performance of slow hand-writers was significantly poorer than that of normal hand-writers for visual perception, visual-motor integration and fine motor coordination tasks. The results of a stepwise regression analysis to identify the strongest predictors of handwriting speed for each group showed that visual-motor integration was a significant and the strongest predictor of handwriting speed for the slow hand-writers. For the normal speed hand-writers, age and fine-motor coordination were the only significant predictors. These results seem to suggest that slow and normal hand-writers responded to the processes required for handwriting through different visual and motor skills. All these results suggest that visual-motor integration skills play a significant role in handwriting in Chinese.

Studies also revealed that children with developmental dyslexia have difficulty in handwriting (Afonso, Suárez-Coalla, & Cuetos, 2015; Martlew, 1992). Developmental dyslexia (DD) is a specific reading impairment which is not accounted for by general intelligence, learning opportunities, general motivation, or sensory acuity (Lyon, Shaywitz, & Shaywitz, 2003). Afonso et al.'s study (2015) revealed that people with dyslexia produced longer writing latencies including inter-letter intervals, writing duration and also produced more errors than their peers without dyslexia in a direct copy transcoding task and a spelling-to-dictation task. Sumner, Connelly and Barnett (2013) found that children with dyslexia copied fewer words per minute than age-matched controls. Their dyslexic children also paused longer within words than their age matched controls did. Sumner et al. further found that the time of within-word pausing was correlated to reading ability only for the children with dyslexia. These results thus suggested that handwriting ability has a close relationship not only with handwriting but also with reading ability.

English-speaking children with developmental dyslexia are also found to have a deficit in visual-motor integration skills (Emam & Kazem, 2014; Hammill, 2004). For example, Emam and Kazem (2014) asked children to complete the Full Range Test of Visual Motor Integration (FRTVMI) (Hammill, Pearson, Voress, & Reynolds, 2006), which includes 18 geometric shapes and figures. Participants were asked to copy all 18 figures on a piece of paper directly. Emam and Kazem found that the performance of children with dyslexia on this particular test was poorer than that of typically-developing children.

Writing difficulty is also a major deficit in Chinese children with dyslexia (Cheng-Lai, Li-Tsang, Chan, & Lo, 2013; McBride-Chang, Chung, & Tong, 2011). Cheng-Lai et al. (2013) for example showed that Chinese dyslexic children performed significantly poorer than-typically-developing Chinese children on a word copying task. The Chinese dyslexic children often wrote characters exceeding the grids.

It is often found that Chinese children with dyslexia have a visual-motor integration deficit, and some researchers found that visual-motor integration skills played a significant role in Chinese writing. For example, Cheng-Lai et al. (2013) investigated the relationships between writing-to-dictation, handwriting performance measured by the Chinese Handwriting Assessment Tool (Li, Leung, Lam, & Li-Tsang, 2008), orthographic awareness, visual-perceptual skills, fine motor skills, visual-motor integration, ocular-motor control and rapid naming in Chinese children with dyslexia. It was found that children with weaker visual-motor integration ability produced more characters exceeding the grid, with more variability in character size (with a larger standard deviation) in their handwriting.

II. Visual-motor integration and Reading

Interestingly some studies found that handwriting practice improved reading ability by fostering orthographic learning (Longcamp, Zerbato-Poudou, & Velay, 2005: Longcamp, Richards, Velay, & Berninger, 2016). Longcamp et al. (2005) indicated that letters were learned through the coordination of a visual configuration and hand movements. This suggests that letters are not represented solely by their visual characteristics but more broadly on the basis of a multimodal representation in which one of the components is sensorimotor in nature. Visual-motor integration can help to combine the visual information of the letter and finger-hand motor component to facilitate letter recognition (Goldstein & Britt, 1994; Santi, Francis, Currie, & Wang, 2015). Recently, Bellocchi et al. (2017) found that kindergarten children's visual-motor integration and phonological awareness skills predicted their reading outcomes in Grade-1. Similarly, Sortor and Kulp (2003) showed that children in the upper quartiles in reading test performed significantly better than children in the lower quartiles in visual-motor integration test. They also found that the score of visual-motor integration was significantly correlated with reading score. Moreover, a meta-analysis study conducted by Hammill (2004) showed visual-motor integration was one of the significant predictors of reading ability in alphabetic language users (e.g., Norway, UK, and USA). It was revealed that visual-motor integration is also associated with reading ability in alphabetic languages

As a logographic writing system, visual configuration of a Chinese character is markedly different from that of an alphabet (Chung, Ho, Chan, Tsang, & Lee, 2011), and orthographic processing skills play a more prominent role in reading Chinese for particularly Chinese children (Ho, Chan, Lee, Tsang, & Luan, 2004). Tan and his colleagues (2005) found that Chinese character copying ability was associated with reading proficiency for beginning-level readers (7-8 years old) and intermediate-level readers (9-10 years old) of Chinese primary school children, and this could explain 22.2% and 19.8% of the variance in reading performance for intermediate-level readers and for beginning-level readers respectively. When phonological processing skills and rapid naming skills were statistically controlled, character-copying still contributed 10.4% and 3.6% of the variance in reading for intermediate and beginning-readers, respectively. Tan et al. concluded that handwriting might influence reading through orthographic awareness and/or motor programming, and handwriting skills contributed more to reading for students with a higher level of reading skills.

However, in their study, some reading-related skills such as orthographic awareness and morphological awareness were not controlled, and thus some researchers argued that these reading-related skills were indeed related to reading skills themselves (Siok & Fletcher, 2001) and handwriting (Wang, McBride-Chang, & Chan, 2014).

It was further reported that handwriting ability in children with dyslexia also predicted the reading performance of these children independently. McBride-Chang et al. (2011) asked 21 Chinese children with dyslexia (7-9 years of age) and 33 age and non-verbal IQ matched Chinese children to copy unfamiliar scripts. The copying materials were words in foreign languages such as Korean, Vietnamese and Hebrew. Results of a hierarchical regression analysis revealed that the copying could explain 6% of the variance in reading when rapid naming, morphological awareness and orthographic skills were statistically controlled. McBride-Chang et al. thus concluded that novel word copying skills reflected pure copying abilities which are important when discussing literacy skills development in Chinese.

However, it is worth noting that copying unfamiliar scripts is similar to copying complex geometric pictures. Visual-spatial configurations of unfamiliar script (e.g. Korean) or geometric pictures are complex. When children are asked to copy unfamiliar scripts or geometric pictures, they cannot make use of language related cognitive skills to undertake these copying tasks. The children have to progressively copy components of unfamiliar stimuli by utilizing and integrating visual-perceptual and motor skills. Therefore copying unfamiliar scripts may not just be the reflection of pure copying ability (the latter argument of which was put forward by

McBride-Chang et al, 2011) but also be the resulting performance of the integrated visual-perceptual and motor processes. The influence of copying unfamiliar stimuli for Chinese reading may be due to the visual-motor integration skills.

In general, it seems that reading skills are directly related to handwriting skills in Chinese children with (Chan et al., 2006; McBride-Chang et al., 2011) or without (Tan et al., 2005; Wang et al., 2014) dyslexia, and that visual-motor integration skills are significantly correlated with handwriting skills in Chinese children (Cheng-Lai et al., 2013; Tseng & Chow, 2000). Reading fluency test was widely used to test the reading efficiency (Shaywitz , Morris, & Shaywitz, 2008; Tan et al., 2005). Some studies found a special connection between reading fluency and visual-motor integration in children with (Emam & Kazem, 2014) and without dyslexia (Bellocchi et al., 2017; Santi et al., 2015) in alphabetic languages. For Chinese children with dyslexia, researchers also found that ability to copy unfamiliar scripts, which was similar to visual-motor integration skill, was correlated with reading fluency (e.g., McBride-Chang et al., 2011). So reading fluency was selected as the outcome measure in the present study. It is therefore reasonable to assume that visual-motor integration skills are also a significant predictor for reading fluency in Chinese children. Naka and Naoi's earlier study (1995) can also lend support to Waterman et al.'s conclusion, in which they revealed that the most effective way of learning to read Japanese Kanji (similar to Chinese) characters is repeated writing. In other words, handwriting has positive influence on reading.

In order to investigate this conjecture, which is the relationship between visual-motor integration skills and Chinese reading ability, the present study asked Chinese children with and without dyslexia to undertake reading, handwriting, visual-motor integration and reading-related cognitive tasks. It was hypothesized that visual-motor integration skills could explain the unique variance in Chinese reading ability when reading-related cognitive skills were statistically controlled.

Method

Participants

61 children were recruited in the study, 19 of which were children with developmental dyslexia (DD group), 18 were typically-developing children with the same chronological age (CA group) and 24 were typically-developing but younger children with the same reading level (RL group). The mean age of the children in the RL group was 12 months younger than the dyslexics. All participants were right-handed with normal intelligence and had normal or corrected-to-normal vision without ophthalmologic or neurological abnormalities. No participant suffered from attention deficit hyperactivity disorder (ADHD). All participants were recruited from three primary schools in Beijing. This study was approved by the Ethics Committee of the Institute of Psychology, Chinese Academy of Science and informed written consent was obtained from the guardian of each participating child.

Combined Raven's Test (CRT) (Li, Chen, & Jin, 1989) and Chinese Character Recognition Test (Wang & Tao, 1996) were administered to screen dyslexic children, which were adopted from the studies conducted with Mandarin-speaking Chinese participants (Meng, Cheng-Lai, Zeng, Stein, & Zhou, 2011; Wang, Bi, Gao, & Wydell, 2010). Combined Raven's Test (CRT) is a standard test for nonverbal intelligence with six sets of twelve items. For each item, participants were shown a matrix with a missing part. Then matrices comprised patterns and participants needed to complete the patterns by selecting from six to eight options. The level of difficulty increases with the test progress. The raw score was the number of correct choices, and the standardized score was transformed from raw score based on the Chinese norms. Chinese Character Recognition Test was adopted to test participants’ character recognition skill. In this test, participants were asked to write down a compound word based on a written target character presented on the sheet. For example, a stimulus, “草_________” is presented to participants, and the participants are required to create a two- to three-character compound word (e.g. 草_______ -> 草地 [grassland] or 大草原 [prairie]). The participants can write down in Pinyin (a phonological coding system that makes use of Roman letters to indicate pronunciations of Chinese characters) instead of the character that they do not know how to write (e.g. “草________” -> 草 dì). In English this would be something like, given a stimuli “**bow**”, participants are asked to write down a compound word such as “**bow**tie” or “rain**bow**”. Each correct response was given one point. Characters were divided into ten groups based on level of reading difficulty. The score for each group was calculated by multiplying the total points by the corresponding coefficient of difficulty. The final score for each participant was the sum of sub-scores for all ten groups.

The inclusion criteria for dyslexics were that their IQs were normal (IQ>85) and Chinese character recognition scores were at least one and half standard deviations below (-1.5*SD*) the average of the children in Grade-4. The chronological age (CA) control children were Grade-4 children with normal vocabulary performance. The reading level (RL) control children were recruited from Grade-3 whose Chinese character recognition scores were the same as those in DD group. The results of the initial screening tests are tabulated in Table 1.

Insert Table 1 about here

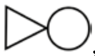
Stimuli & Procedure

The stimuli consisted of a battery of tests covering reading fluency, word copying, visual-motor integration, phonological awareness, orthographic processing, rapid naming and morphological awareness. Total testing time was approximately 50 minutes. Tests were randomly presented to each child during the testing. Each test is described below in detail.

Reading Chinese Character test. This test was developed by Qian, Deng, Zhao, and Bi (2015) which includes160 high frequency Chinese characters that were selected from the Modern Chinese Frequency Dictionary (1986). The children were asked to read each character as quickly and accurately as possible, and the test lasted one minute. The number of correct responses was summed up to represent the children’s reading ability. The reliability of this test (Cronbach’s alpha) was 0.97.

Two-Character Chinese Word copying test. A similar copying test employed by Tan et al. (2005) was used. 90 simple two-character Chinese words were selected from Grade-3 textbooks. Children were given all words printed on one sheet, and were asked to copy down as quickly and accurately as possible within 3 minutes. One point was given when a word was correctly copied, and reliability of this test

(Cronbach's alpha) was 0.88.

Visual-motor integration test. A figure drawing task that is similar to the Picture Quality Scale (Miyahara, Kotani, & Algazi, 1998) was administered. Six geometric figures were printed on a sheet of paper, and the participating children were asked to copy the figures without a time-limit. The geometric figure stimulus becomes increasingly more complex (e.g., , ). It is assumed that copying these geometric figures does not require language related skills such as phonological, orthographic or semantic processing skills, and that the task can assess children's visual-motor integration skills. Three undergraduate students evaluated the children's performance on the task according to the four criteria, i.e., the ratios, orientation, symmetry and position on a 5-point (1-5) scale. The evaluators' scores of the six stimuli on the four criteria for each participant's performance were added (score range=24-120) and average scores of three evaluators was regarded as final scores. The inter-raters reliability of this test was 0.94.

Phonological awareness test. An oddball paradigm from Qian et al. (2015) was adopted. Within a trial, three Chinese single-characters were presented orally by the experimenter. The participating children were asked to point to a phonologically odd item among them. There were three types of oddity, which were onset, rime and lexical tone respectively. For example, the third syllable was the correct (oddity) answer of /*Hu3, Gu3 Shui3/* because "Hu3" and "Gu3" had the same rime "u", which was different from "Shui3". Ten trails for each type of oddity were presented. The number of correct responses was recorded. The reliability of this task (Cronbach's alpha) was 0.76.

Orthographic processing skills test. A character judgment task from Qian and Bi (2014) was adopted. This test consists of 40 real Chinese characters, 20 pseudo-characters and 20 non-characters. Pseudo-characters consisted of two position-legal radicals (e.g. ). The radicals of non-characters (e.g. ) were in illegal positions. The task was presented on a computer screen, whereby after a 500ms fixation, a stimulus character was presented in isolation in the center of the computer screen. The participating children were asked to judge whether a presented item was a real Chinese character or not by pressing different buttons. Although pseudo-characters and non-characters are not real characters, pseudo-characters conformed to orthographic rules while non-characters did not. So, the different performance between pseudo-character and non-character judgment reflected the orthographic skills. Therefore, the reaction times of pseudo-characters and non-characters were recorded.

Rapid naming task. This task (Denckla & Rudel, 1976) consisted of 5 digits randomly selected from 0 to 9 (e.g., 9, 4, 7, 6, 2). Digits were presented visually in random order on a six row × five column grid. The children were asked to name each digit in sequence as quickly as possible and read all digits twice. Naming latencies were recorded and the score was the average time of the two readings. The test-retest reliability of this task was 0.78.

Morphological awareness test. A word creation task was similar to that used by Shu et al. (2006). In this task, 12 two-syllable Chinese words (e.g., 草地/*Cao3*

Di4/[meaning grassland]) were presented on A4 paper. Within that two-morpheme word, one morpheme was identified (e.g., 草/Cao3/). Children were asked to produce two words containing the target morpheme. One of the morphemes had the same meaning as the target morpheme (e.g., 小草/Xiao3 Cao3/ [meaning grass]). The other morpheme had a different meaning from its original meaning (e.g., 草率/Cao3 Shuai4/ [meaning haste]). The maximum score was 24 (two points per trial) and the reliability of this test was 0.73.

Results

Word Copying, Visual-Motor Integration and Reading-Related Tests

Table 2 shows the results of one-way ANOVAs as well as post-hoc Bonferroni tests.

Insert Table 2 about here

Results showed that the DD-group performed significantly poorer than the CA-group in all the tests administered except for phonological awareness and pseudo-character judgment tests, but similarly to the RL-group (see Table 2). The results thus suggested that DD-group had deficits in reading, morphological awareness, non-character judgment, rapid naming and word copying. The DD-group performed significantly poorer than both the CA- and RL-groups in the visual-motor integration task, while there was no difference between CA- and RL-groups, suggesting that visual-motor integration deficit was a kind of inherent deficit in Chinese children with developmental dyslexia, and was not influenced by reading experience.

Correlation Coefficients among All Measures

The relationships between variables were analyzed using Pearson's correlation, the results of which are shown in Table 3.

Insert Table 3 about here

As shown in Table 3, children's reading skill was associated with phonological awareness, pseudo-character (RTs)/ non-character (RTs) judgment, morphological awareness, rapid naming, word copying and visual-motor integration skills respectively. Most interestingly there was no significant correlation between word copying and visual-motor integration skills. Possible reasons for this non-significant correlation are explored in the discussion.

Hierarchical Regression Analyses

In order to examine the effects of word copying and visual-motor integration in reading ability separate hierarchical regression analyses were conducted with reading ability, word copying and visual-motor integration as the independent variables respectively. Age and intelligence were controlled, which entered in the regression models as Step 1. Then, phonological awareness, morphological awareness, rapid naming, reaction time of pseudo-character and non-character entered in regression models as Step 2. Finally, word copying and visual-motor integration entered in two separate regression models as Step 3.

Insert Table 4 & 5 about here

Results showed that word copying could explain 16% (df=60, β=0.42, p<0.01) of variance in reading. But word copying did not account for additional variance in reading when reading-related cognitive skills, i.e., phonological awareness, morphological awareness, rapid naming, reaction time of pseudo-character and non-character, entered as Step 2, suggesting that word copying did not have contribution to reading ability independently. Visual-motor integration could account for 14% (*df*=60, β=0.32, *p*<0.01) of the variance in reading. Moreover, even when reading-related cognitive skills and word copying were controlled visual-motor integration could still explain 8% (*df*=60, β=0.27, *p*<0.05) of the variance. It indicated that visual-motor integration exerted a significant and unique contribution over Chinese reading.

Discussion

The present results can be summarized as follows: (i) the DD-group performed poorer than the CA-group but similarly to the RL-group on reading, orthographic processing skills, rapid naming, morphological awareness and word copying; (ii) the DD-group performed significantly poorer than both the CA- and the RL-groups on visual-motor integration; (iii) Reading performance significantly correlated with both word copying and visual-motor integration skills, importantly word copying and visual-motor performance skills were not interrelated (this is discussed in detail below), (iv) Word copying explained 16% of the variance in reading when cognitive skills were not controlled. However, when cognitive skills were controlled word copying did not contribute uniquely to reading; and (v) visual-motor integration explained 8% of the unique variance in reading when age, intelligence and cognitive skills were controlled.

Thus, dyslexic children had a poorer word copying ability than age matched children, and the performance on word copying significantly correlated with reading performance and cognitive skills. The copying (word) materials in the present study were selected from textbooks that the participating children have used, and thus they were familiar with the stimuli's phonological, orthographic and semantic information. Further there were significant correlations among word copying and reading related skills including orthographic processing, morphological awareness and rapid naming, and thus in order to ascertain unique contribution of word copying to reading, the cognitive skills (e.g., morphological awareness, rapid naming, phonological awareness) were statistically controlled in the current study. The results suggested that word copying did not explain a unique variance in reading performance, indicating that word copying was not an independent predictor of reading and the relationship between word copying and reading was influenced by reading related skills, which was not consistent with previous studies (e.g., Tan et al., 2005). The discrepancy in the results between Tan et al.'s study and the current study can be simply due to the fact that Tan et al. did not control reading-related cognitive skills such as morphological awareness and orthographic processing when measuring/analyzing the word copying skills, and therefore the significant link between reading and copying skills might have emerged inappropriately.

The copying materials used in McBride-Chang et al.'s (2011) study were selected from Korean, Vietnamese and Hebrew, and the orthographic structures and print-sound mappings of these scripts are different from those of Chinese characters.

Furthermore, since children in Hong Kong were unfamiliar with these copying materials, McBride-Chang et al.'s rationale for using these foreign scripts (to Chinese participating children) was that their participating children were not able to access phonological, orthographic and semantic information inherent to these scripts. Thus the linguistic cognitions for Chinese could not exert their influence over the copying task in McBride-Cheng et al.'s study.

A close inspection into the stimuli used by McBride-Chang et al. for copying revealed the following: (a) there are some orthographic similarities between the Chinese characters and the copying stimuli in Korean, and (b) Vietnamese uses European alphabets though requiring diacritic symbols. Only Hebrew stimuli look very different from the Chinese characters. However, the authors noted, "….We incorporated Hebrew writing only approximately halfway through our study, so that task was administered to only a subset of the children …" (McBride-Chang et al., 2011, p.425). Therefore their copying stimuli, in particular, in Korean and Vietnamese might not have been as unfamiliar to the participating Chinese children in Hong Kong as the authors hoped. Therefore the data from McBride-Chang et al.'s copying task might not warrant their assertion that copying skills in their study reflected pure copying abilities.

In the present study, it was hypothesized that visual-motor integration deficit might be another possible basic deficit in Chinese children with developmental dyslexia. As shown in the results the dyslexic children in the current cohort performed significantly poorer on the visual-motor integration test than the CA-group, which is consistent with the previous study conducted in Arabic in Oman (Emam & Kazem, 2014). Furthermore, the current study found that the Chinese dyslexics in the current cohort also performed poorer on the visual-motor integration task than the RL-group, indicating that a visual-motor integration deficit may not be caused by a lack of reading experience, and instead may be a kind of inherent deficit in Chinese children with developmental dyslexia.

The current results also revealed that visual-motor integration was not related with word copying. In the word copying task, the participants copied familiar Chinese characters whose phonological, morphological and orthographic information were known to the participants. In contrast in the visual-motor integration test, the participants were asked to copy hitherto unseen complex geometric figures without any linguistic information. In the present results, the correlations between reading-related cognitive skills and word copying were moderate (range of correlation coefficients: 0.17-0.44), but much smaller with visual-motor integration (range of correlation coefficients: 0.11-0.26). This suggests that copying familiar scripts might depend on reading-related cognitive skills while it did not depend on visual-motor integration. Visual-motor integration is known to be dependent on basic visual perception (Decker, Englund, Carboni, & Brooks, 2011). Furthermore, the poor performance of the children with dyslexia on word copying test might be due to lack of reading experience/lower level of attainment in reading. The visual-motor integration skills appear to develop very early in typically developing children. Although the children in the RL-group were younger than the children in the

DD-group, they still had similar visual-motor integration ability as those in the children in the CA-group. Thus, the correlation between word copying and visual-motor integration was not significant because these two copying tasks may depend on different cognitive skills.

The current study indicated that word copying and visual-motor integration have different predictive effects on reading performance. Reading-related cognitive skills played important roles in the relationship between reading and copying familiar characters. Only visual-motor integration exerted its unique contribution to reading performance, especially to reading Chinese when cognitive skills and word copying were controlled. Visual-motor integration is thought to combine the visual-spatial information of the character and finger-hand motor component (Gabbard, Goncalves, & Santos, 2001). Considering the high, nonlinear visual complexity of Chinese characters (Tan et al., 2005), Chinese children are forced to discriminate differences in structures of characters when they read in Chinese. Identifying the visual-spatial components can help not only Chinese children to learn the shape of characters but also to track their stroke sequences of characters when they learn to read (Maldarelli, Kahrs, Hunt, & Lockman, 2015). Thus, visual-motor skill might be especially important for Chinese children's reading ability. On the other hand, neuroimaging studies on motor memory showed that written Chinese character recognition is mediated by the posterior portion of the left middle frontal gyrus (Tan, Laird, Li, & Fox, 2005), suggesting that motor system may have influence on Chinese reading. Studies on functional connectivity analyses of neural pathways in reading showed that the visual presentation of alphabetic letters but not pseudo-letters activated an area of the left premotor cortex (BA6) which was also activated when the letters were being written by dictation (Longcamp, Anton, Roth, & Velay, 2003). Supplementary motor cortex, along with Broca’s area (i.e., the ventral prefrontal area) is relevant to grapheme-to-phoneme conversions (Fiez, Balota, Raichle, & Petersen, 1999) and subvocal rehearsal component of phonological process (Chein, Ravizza, & Fiez, 2003). Similarly, He et al. (2003) showed that reading in Chinese recruited a neural circuit linking Broca’s area in the supplementary motor area and premotor cortex. Visual-motor integration coordinated finger motion and visual stimulation to form handwriting mode and then facilitate the premotor and supplementary motor areas (Ledberg, Bressler, Ding, Coppola, & Nakamura, 2007). Eventually, motor system, along with phonological network, is able to enhance word recognition in cognitive system and Chinese reading (Perfetti & Tan, 2013; Zhang et al., 2017).

In summary, the current study found that Chinese children with developmental dyslexia exhibited deficits both in word copying and visual-motor integration. Moreover, visual-motor integration uniquely contributed to reading which was independent of, and over and the above the contribution of word copying to reading, suggesting that visual-motor integration, not word copying, played an essential and independent role in Chinese reading. Thus, by combining motor function and visual process, visual-motor integration can help children to acquire motor information of Chinese characters that they are reading. These motor information facilities the consolidation process of lexical representations in the cognitive system. As a result, children with better visual-motor integration ability perform better in Chinese reading.

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Tables

Table 1

Means(M), Standard Deviations(SD) and ANOVAs For Information Of Participants

	DD group (N=19)	CA group (N=18)	RL group (N=24)	*F*
	M (SD)	*M (SD)*	*M (SD)*	
Age (years)	9.10 (0.31)	9.10 (0.13)	8.01 (0.28)	127.39**
CCRT [a]	1404.18 (244.77)	2377.81 (112.36)	1399.43 (189.67)	165.33**
CRT [b]	111.63 (17.75)	114.06 (9.86)	114.88 (9.10)	0.37

Note: * p<0.05, **p<0.01. [a] *CCRT* Chinese Character Recognition Test, [b] *CRT* Combined Raven's Test.

Table 2

Means(M), Standard Deviations(SD) and ANOVAs(Fs) for All Measures for Children with and without Dyslexia

Variables	DD group	CA group	RL group	*F*	Post hoc comparisons
	M (SD)	*M (SD)*	*M (SD)*		(p<0.05)
Reading fluency	70.79 (16.34)	91.11 (11.92)	73.96 (15.55)	**10.15****	**DD=RL<CA**
Phonological awareness	16.26 (4.36)	18.78 (5.47)	17.42 (2.81)	1.63	DD=CA=RL
Pseudo-character RT（ms）	1176.62 (255.93)	1053.96 (196.29)	1174.93 (242.83)	1.70	DD=CA=RL
Non-character RT（ms）	940.80 (142.84)	839.64 (119.73)	952.87 (122.29)	**4.53***	**CA<DD=RL**
Rapid naming (s)	12.88 (2.34)	10.68 (2.03)	12.95 (2.67)	**5.55****	**CA<DD=RL**
Morphological awareness	13.47 (3.34)	16.94 (3.19)	14.54 (3.36)	**5.35****	**DD=RL<CA**
Word copying	29.32 (8.48)	34.28 (5.37)	28.25 (5.47)	**5.26****	**DD=RL<CA**
Visual-motor integration	101.21 (6.80)	107.78 (6.75)	106.92 (6.32)	**5.63****	**DD<CA=RL**

Note: * *p*<0.05, ***p*<0.01

Table 3

Correlations among All Individual Tasks

	1	2	3	4	5	6	7	8	9	10
1.Age	-	-0.37**	0.43**	0.26*	-0.30**	-0.42**	-0.38**	0.17	0.39**	0.03
2. Intelligence		-	-0.05	-0.05	0.06	0.05	0.01	0.12	0.03	0.23*
3.Reading fluency			-	0.33**	-0.24*	-0.37**	-0.45**	0.42**	0.29**	0.26*
4.Phonological awareness				-	-0.15	-0.28**	-0.35**	0.46**	0.17	0.11
5.Pseudo-character RT					-	0.78**	0.13	-0.24*	-0.29**	-0.09
6.Non-character RT						-	0.34**	-0.36**	-0.38**	-0.18
7. Rapid naming							-	-0.52**	-0.44**	-0.26*
8.Morphological awareness								-	0.28**	0.21*
9. Word copying									-	0.16
10.Visual-motor integration										-

Note: * *p*<0.05, ***p*<0.01

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Table 4

Hierarchical Regressions Explaining Reading by Word Copying

Step	*⊿R²*	*β*	*t*
Age and Raven (CRT) controlled			
Step 1	0.08*		
1.Age		0.30	2.69**

1. Raven (CRT)		0.10	0.94
Step 2	0.16^{**}		
2.Word copying		0.42	3.38^{**}
Age, Raven (CRT) and reading related cognitive skills controlled			
Step 1	0.06^{*}		
1.Age		0.31	2.82^{**}
1. Raven (CRT)		0.13	1.18
Step 2	0.27^{**}		
2.Phonological awareness		0.04	0.33
2.Character RT		0.11	0.47
2.Pseudo-character RT		0.01	0.02
2.Non-character RT		-0.09	-0.37
2.Rapid naming		-0.59	-4.87^{**}
2.Morphological awareness		-0.17	-1.43
Step 3	0.02		
3. Word copying		0.17	1.15

Note: * p<0.05, ** p<0.01

1

Table 5

Hierarchical Regressions Explaining Reading by Visual-Motor Integration

Step	$\triangle R^2$	β	t
Age and Raven (CRT) controlled			

Step 1	0.08*		
1.Age		0.30	2.69**
1. Raven (CRT)		0.10	0.94
Step 2	0.14**		
2.Visual-motor integration		0.32	3.16**
Age, Raven (CRT), reading related cognitive skills and word copying controlled			
Step 1	0.09*		
1.Age		0.31	2.82**
1. Raven (CRT)		0.13	1.18
Step 2	0.27**		
2.Phonological awareness		0.04	0.33
2.Character RT		0.11	0.47
2.Pseudo-character RT		0.01	0.02
2.Non-character RT		-0.09	-0.37
2.Rapid naming		-0.59	-4.87**
2.Morphological awareness		-0.17	-1.43
Step 3	0.02		
3. Word copying		0.16	1.13
Step 4	0.08*		
4. Visual-motor integration		0.27	2.70*

Note: * $p<0.05$, ** $p<0.01$

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