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Visuomotor integration and executive functioning are uniquely linked to Chinese word reading and writing in kindergarten children

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Abstract This cross-sectional study examined the associations of visuomotor integration and executive functioning with Chinese word reading and writing in kindergarten children. A total of 369 Chinese children (mean age = 57.99 months; 55% of them were girls) from Hong Kong, China, completed tasks on visuomotor integration, executive functioning, and Chinese word reading and writing. Children also completed tasks on rapid automatized naming, and their mothers provided child and family background information. Hierarchical regression analyses revealed that, controlling for child age, gender, and rapid automatized naming and maternal education, both visuomotor integration and executive functioning were uniquely linked to Chinese word reading and writing. Findings highlighted the importance of visuomotor integration and executive functioning in understanding the development of Chinese word reading and writing in early years, and the utility of targeting visuomotor integration and executive functioning to help kindergarten children to learn to read and write in Chinese.

Keywords Chinese literacy · Executive functioning · Kindergarten children · Reading and writing abilities · Visuomotor integration

Introduction

Reading and writing, also referred to as literacy, are important skills to master in modern societies. Reading and writing abilities in early childhood are robust precursors of literacy achievement and academic success in middle childhood and beyond (Whitehurst & Lonigan, 1998, 2001). Given that children vary in their

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reading and writing abilities from a very young age, it is important to examine the correlates of reading and writing in early years (Georgiou, Parrila, Cui & Papadopoulos, 2012). Emerging research indicates that reading and writing are highly complex processes that involve not only domain-specific skills, such as phonological, semantic, and syntactic processing, but also domain-general skills, such as visuomotor integration (VMI) and executive functioning (EF; Cameron, Cottone, Murrah & Grissmer, 2016; De Franchis, Usai, Viterbori & Traverso, 2017). Existing work that links VMI and EF to reading and writing, however, are mostly based on alphabetic languages, especially English (Becker, Miao, Duncan & McClelland, 2014; Cameron et al., 2012). Although about one fifth of the world's population lives in China (United Nations, 2017) and all children in China have to study Chinese as a formal subject in school (Ministry of Education of The People's Republic of China 2015), little is known about whether VMI and EF uniquely contribute to Chinese word reading and writing. Moreover, unlike English, Chinese has a logographic and morphosyllabic writing system that includes more than 40,000 distinguishable characters (Liu, Chuang & Wang, 1975). Because of the visual complexity of Chinese characters (Kao, 2006) and the lack of consistent linkages between their shapes and sounds (Shu, Chen, Anderson, Wu & Xuan, 2003), VMI and EF may be particularly important in information processing, verbal articulation, and fine motor coordination during reading and writing Chinese characters. Expanding upon prior work, the goal of the present study was to fill gaps in the literature by examining whether VMI and EF were uniquely associated with Chinese word reading and writing in kindergarten children from Hong Kong, China.

VMI and Chinese word reading and writing

VMI refers to visual-motor skills that integrate visual-perceptual information and fine motor movements to support the execution of higher-order functions (Hammill, 2004). VMI typically involves perceiving and processing spatial units, constructing and manipulating mental representations, and reproducing them in written forms through synchronized, hand–eye coordination (Cameron et al., 2015). Students of alphabetic languages argue that VMI may play a crucial role in the development of early literacy (Carlson, Rowe & Curby, 2013; Grissmer, Grimm, Aiyer, Murrah & Steele, 2010): When children are learning to read and write, VMI may help children to link points, lines, and curves in particular spatial orientations to form letters, to organize letters in particular orders to form words, and to reproduce letters and words using fine motor movements. Moreover, given its relevance to information transfer across modalities (Sigrist, Rauter, Riener & Wolf, 2013; Zmigrod & Hommel, 2013), VMI may help children to read and write by coordinating other relevant cross-modality processes, such as connecting orthographic and phonological information and deriving sounds from prints.

Indeed, recent research has linked VMI to literacy achievement in early childhood. For example, VMI, measured using such copying tasks as the Beery Visuomotor Integration Assessment (Beery &Beery, 2004), has been correlated with phonological awareness, print knowledge, word reading, name writing, and written expression in English scripts among kindergarten children (Becker et al., 2014;

Cameron et al., 2012). According to these authors, the visual-motor skills required to master the copying tasks may tap into children's general abilities to receive visual signals and respond with corresponding fine motor movements, which are likely to be equally important in mastering reading and writing tasks. Findings based on English scripts may not necessarily be generalizable to Chinese scripts, however, especially considering the unique features of the Chinese writing system.

The basic graphic unit of the Chinese writing system constitutes a written character representing a morpheme and a syllable, which are not linked together by a consistent mapping rule (Kao, 2000; Shu, McBride-Chang, Wu S & Liu, 2006). Each character is different from thousands of other characters in terms of strokes (e.g., 一, 丨, 丿) and subcomponents (e.g., 几, 冖, 叉). These strokes and subcomponents may be combined to form a character (e.g., 凡, 叉, 日). They may also be combined to form structures called radicals (e.g., 宀, 广, 魚) and phonetics (e.g., 八, 黃, 羊), which are arranged in different spatial orientations, often from left-to-right, top-to-bottom, and outside-to-inside, to form a character (e.g., 穴, 廣, 鮮). Therefore, an understanding of stroke forms and subcomponent configurations, particularly how they can be combined, is critical to the acquisition of Chinese word reading and writing. In fact, over time, the emphasis of children's writing progresses from strokes and subcomponents to radicals and phonetics to the whole characters (Shi, Li, Zhang & Shu, 2011). A growing awareness of radicals (e.g., 木, meaning wood), which conveys information about the meaning of a character (e.g., 林, 樹, and 榆 are all related to wood), and phonetics [e.g., 青(cing1)], which conveys information about the pronunciation [e.g., 清(cing1), 晴(cing4), and 靖(zing6) all sound similar], also helps children to learn new characters more effectively (Ho, Yau & Au, 2003).

Despite these general rules, reading and writing Chinese words remain a visually complex and cognitively demanding task. First, different strokes and subcomponents are combined in an inflexible and non-intuitive order. In order to write a character correctly, children have to memorize, sequentially, how strokes and subcomponents are amalgamated to form radical and phonetics and the whole character. Second, a functional reader can recognize about 4500 characters (Liu et al., 1975), many of which are visually similar. The addition of one stroke [e.g., 天(tin1), meaning sky, versus 大(daai6), meaning big], or the slight alternation of the spatial orientation of it [e.g., 天(tin1), meaning sky, versus 夭(jiu2), meaning die], can completely change the meaning and pronunciation of a character. Finally, only 80% of all Chinese characters are radical-phonetic compounds, and there is huge variability in the usefulness of the information conveyed by radicals and phonetics across characters (Shu et al., 2003). For example, although the radical meaning is directly related to the character meaning in about 80% of radical-phonetic compounds, the phonetic sound was identical to the character sound in only about 20% of them. Therefore, initial learning of Chinese words often involves arbitrary coupling of visual forms, oral labels, and conceptual meanings, typically through explicit teaching and repeated practice.

Considering the visual complexity of Chinese characters, VMI may be particularly important in understanding the development of Chinese word reading and writing. Kao (2006), for example, argued that learning Chinese characters involves internalizing the visual-motor aspects of Chinese word writing. Tan, Spinks, Eden, Perfetti, and Siok (2005) further suggested that copying of Chinese characters may facilitate such internalization processes. Indeed, two studies showed that kindergarten children's VMI, indicated by their abilities to copy unfamiliar prints, such as Hebrew, Korean, and Vietnamese, was linked to Chinese word writing (Wang, McBride-Chang & Chan, 2014; Wang, Yin & McBride, 2015). These two studies, however, were conducted with kindergarten children from Beijing, China, who used simplified Chinese scripts and spoke Mandarin. We were interested in whether VMI was relevant to Chinese word reading *and* writing in kindergarten children from Hong Kong, as they use traditional Chinese scripts, which prescribe a more complex amalgamation of strokes and subcomponents than do simplified Chinese scripts (e.g., 對, 電, 華 versus 对, 电, 华), and speak Cantonese, which utilizes six to nine tones of the same sound, instead of four in Mandarin, to indicate different characters. Learning to read and write Chinese words may be more complex and demanding, and thus require even higher levels of VMI, in Hong Kong than in Beijing.

Instead of assessing children's abilities to copy unfamiliar prints existing in other languages (e.g., Hebrew, Korean, and Vietnamese), we also used a relatively culture-free measure, the Beery Visuomotor Integration Assessment (Beery, Buktenica & Beery, 1997), to assess children's abilities to copy increasingly complex geometric figures about which they had no prior cognitive or visual-orthographic knowledge. Such pure copying skills may capture more primitive, visual-motor skills that are relevant to Chinese word reading and writing.

EF and Chinese word reading and writing

EF refers to skills that coordinate multiple cognitive processes to govern thoughts, emotions, and behaviors (Blair, 2016; Diamond, 2013). It allows for conscious control of thoughts and emotions, planning and problem solving, and other goal-directed behaviors, especially in response to complex stimuli and challenging environments. EF is theorized to be composed of three core components, namely working memory, inhibitory control, and cognitive flexibility (Miyake et al., 2000). Working memory refers to the ability to hold and manipulate mental representations, inhibitory control refers to the ability to suppress unthinking or inappropriate responses, and cognitive flexibility refers to the ability to choose from potentially conflicting behavioral alternatives and shifting focus to the mental framework that is most relevant to the task at hand.

Although the three subcomponents of EF can be understood as diversity (Miyake et al., 2000), their roles seem to be less differentiated and specialized in early childhood (Lee, Bull & Ho, 2013; Miyake & Friedman, 2012; Willoughby, Wirth & Blair, 2012). Moreover, evidence from neurological research indicates that the prefrontal and parietal cortex, which supports EF, continues to develop from infancy through early adulthood (Blakemore & Choudhury, 2006; Diamond, 2013; Garon, Bryson & Smith, 2008). In empirical work, EF, measured as either one composite score (Espy, Sheffield, Wiebe, Clark & Moehr, 2011; Welsh, Nix, Blair, Bierman & Nelson, 2010; Zaitchik, Iqbal & Carey, 2014) or as multiple indicators (Chung &

McBride-Chang, 2011; Lan, Legare, Ponitz, Li & Morrison, 2011), has been linked to children's self-management, understanding of rules and instructions, and actual learning abilities. EF has also been positively associated with English word reading and spelling in kindergarten children (Berlin & Bohlin, 2002; Blair & Razza, 2007; Dilworth-Bart, 2012; Ponitz, McClelland, Matthews & Morrison, 2009). In fact, recent research has indicated that both EF and VMI are uniquely correlated with English literacy skills in kindergarten children (Becker et al., 2014; Cameron et al., 2012). Combined with the literature on VMI reviewed above, these findings suggested that EF, as well as VMI, may be implicated in the integration of different perceptual, spatial, and cross-modal processing networks when children read and write (Blair, 2016; Rayner, Foorman, Perfetti, Pesetsky & Seidenberg, 2001). In other words, EF and VMI may be domain-general skills that constitute the cognitive basis for reading and writing, at least in alphabetic languages.

Less attention has been directed to the potential impact of EF on Chinese word reading and writing in kindergarten children. As noted, however, reading and writing Chinese characters, especially in traditional Chinese scripts and in Cantonese, are both visually complex and cognitively demanding. To complicate matters further, some Chinese characters not only look similar, but also sound similar or even identical. For example, the characters 拍 (paak3), meaning hit, 伯 (baak3), meaning older men, and 怕 (paa3), meaning afraid, differ only by their radicals and rhyme with one another. Also, the characters 澡(cou3), meaning wash, 噪(cou3), meaning noisy, and 燥(cou3), meaning angry, differ only by their radicals and have the exact same pronunciation. There are also characters that look alike, but sound different [e.g., 人(jan4), meaning people, versus 入(jap6), meaning enter], and characters that look different, but sound similar [e.g., 車(ce1), meaning cars, versus 遮(ze1), meaning cover] or exactly the same [e.g., 奇(kei4), meaning wonderful, versus 祈(kei4), meaning pray].

To distinguish these confusable characters, children need to simultaneously hold and manipulate the information about multiple characters in their working memory (Shu et al., 2006). They also need to shift flexibly between sources of orthographic, phonological, and semantic information, and supress the mental representation of a specific characteristic of a character, be it the shape, sound, or meaning, in favour of another. Considering its integrated functions of directing thoughts and behaviors (Blair, 2016; Diamond, 2013), EF is likely to be facilitative of Chinese word reading and writing. Indeed, two studies demonstrated that subcomponents of EF were linked to Chinese word reading in kindergarten children from Hong Kong (Chung & McBride-Chang, 2011) and from Beijing (Lan et al., 2011). However, the joint impact of EF *and* VMI on Chinese word reading *and* writing remains underexplored. As both reading and writing involve processing relevant information and suppressing irrelevant one in working memory (which require EF), as well as coordinating information about shapes and sounds and translating it into body movements (which require VMI), EF and VMI may contribute independently to the mastery of these two important literacy skills.

The present study

To recap, the goal of the present study was to examine VMI and EF as unique correlates of Chinese word reading and writing in kindergarten children from Hong Kong. Based on prior theory and research, we hypothesized that VMI and EF would be positively and uniquely associated with Chinese word reading and writing. We controlled for child age and gender, as older children and girls tend to have better literacy skills (Otto, 2008). We also controlled for maternal education, as an index of family socioeconomic status (Shavers, 2007), as children from high- and middle-class families tend to know more words beginning from early years (Bhattacharya, 2010). Finally, we controlled for rapid automatized naming (RAN), or the ability to quickly and accurately name a series of familiar stimuli, such as digits, letters, objects, and colors, as RAN has been identified as a strong predictor of Chinese word reading and writing in earlier studies (Chan, Ho, Tsang, Lee & Chung, 2006; Chung et al., 2008; McBride-Chang & Ho, 2005). In fact, RAN has been described as "a microcosm or mini-circuit of the later developing reading circuitry" (Norton & Wolf, 2012, p. 430), as it taps into many cognitive processes that are crucial for language production, including processes that direct attention to letters and words, associate visual stimuli with relevant orthographic and phonological representations stored in the mental lexicon, and integrate multiple sources of information to inform semantic and syntactic processing (Bowers & Newby-Clark, 2002; Georgiou et al., 2012). Therefore, we controlled for RAN in order to isolate the potentially unique contributions of VMI and EF to Chinese literacy achievement in early childhood.

Method

Participants

Three hundred and sixty-nine second-year children (and their mothers) from 10 kindergartens in Hong Kong participated in the present study. Kindergartens in Hong Kong varied highly in size, with the number of students ranging from 100 to 300. Reflecting the experiences of most children in Hong Kong, all participating kindergartens used traditional Chinese scripts and Cantonese as the medium of instruction. All participating children learned Chinese characters with a "look and say" method, without the assistance of a phonetic system, such as *Pinyin*, as in the case of other regions of China.

To ensure that families from diverse socioeconomic backgrounds were recruited, a stratified sampling approach was adopted. Based on their median monthly household incomes (Hong Kong Census and Statistic Department, 2015), the 18 geographic districts of Hong Kong were first stratified into high, middle, and low socioeconomic strata. Cold calls were then made until three kindergartens in each stratum agreed to recruit families for the study. Two kindergartens recruited from the high socioeconomic stratum turned out to be small in size. Therefore, one more kindergarten was recruited from that stratum to strive for a more balanced distribution of families from different socioeconomic backgrounds. The final sample included 126, 152, and 91 families from high (four kindergartens), middle (three kindergartens), and low (three kindergartens) socioeconomic strata, respectively. Mothers provided child and family demographic information through questionnaires. The mean maternal education was 3.05 ($SD = 1.14$), representing high school completion on a 5-point scale, ranging from 1 (*elementary school education*) to 5 (*postgraduate education*). The mean age of children was 57.99 months ($SD = 4.77$). Fifty-five percent of them were girls ($n = 204$).

Procedures

Parental permission for child participation was obtained before data collection. Data collection began at the beginning of the second school term and lasted for about 3 months. To prevent fatigue, children were tested individually within a 45-min session in their own kindergartens, with short breaks being scheduled between tests. All tests were administered by trained research assistants and adult student helpers, as described below.

Measures

VMI

The short form of the Beery-Buktenica Developmental Test of Visual-Motor Integration (Beery et al., 1997), which taps into children's fine motor speed, accuracy of eye-hand coordination, and integration of visual and motor abilities, was used to measure visual-motor skills. In the task, children were asked to reproduce 21 geometric figures using paper and pencil. As the test progressed, the figures became more complex and more difficult to copy. Children were asked to first scribble and then imitate figures, including vertical and horizontal lines, simple shapes (e.g., circles, squares), intersecting lines, and multiple, overlapping shapes. One point was given for a correctly completed shape, and zero point was given for an incorrectly completed shape. The Spearman-Brown split-half reliability was .73.

EF

The Hearts-And-Flowers Task (Calderon, Jambaqué, Bonnet & Angeard, 2014; Davidson, Amso, Anderson & Diamond, 2006) was used to measure EF. This task included three testing blocks: the congruent block (12 trials; indicating working memory), the incongruent block (12 trials; indicating inhibitory control), and the mixed block (20 trials; indicating cognitive flexibility). Either a heart or a flower was displayed on the right or left side of a computer screen for 2500 ms. The response buttons for the left and right sides were the "z" and "m" keys on the computer keyboard, respectively, indicated by colored stickers. In the congruent block, children were instructed to press the button on the same side as the heart or the flower. In the incongruent block, children were asked to press the button on the side opposite to the heart or the flower. In the mixed condition, children were asked to flexibly switch between those two rules (same or opposite side), where the heart or the flower might appear. Each block was preceded by its own instruction and demonstration, followed by four practice trials. Given that the factor structure of EF tends to be unstable in early years (Lee et al., 2013; Miyake & Friedman, 2012; Willoughby et al., 2012), the mean accuracy scores of the three blocks were subject to a principal component analysis. The results revealed only one component with an eigenvalue exceeding 1, explaining 54.1% of the variance. The congruent, incongruent, and mixed blocks also loaded strongly on this component (loadings = .69, .78, and .73, respectively). Because the three blocks included different numbers of trials, their scores were standardized before being averaged to indicate EF abilities.

RAN

A test developed in previous research was used to measure RAN (Shu et al., 2006). The measure included five rows of five Arabic digits (e.g., 2, 4, 6, 7, and 9), printed on paper in random order. Children were required to read the digits aloud as quickly and accurately as possible. Each child did the test twice, and the mean time in seconds required to complete the two trials was calculated. The test–retest reliability was .83.

Chinese word reading

A combination of 30 Chinese single-character words and 30 Chinese two-character words was used to assess children's word reading abilities. These words were selected, given prior research indicating that they are commonly seen in reading materials for Chinese kindergarten children and that they constitute a reliable and valid measure in Hong Kong children (Chung & McBride-Chang, 2011; McBride-Chang & Ho, 2000). Children were asked to read aloud these words, which were ordered in ascending order of difficulty. One point was given when children pronounced the word correctly, and zero point was given for an incorrect response. The Cronbach's alpha was .97.

Chinese word writing

A dictation task developed for the present study was used to access children's Chinese word writing abilities. In the task, children were requested to write seven Chinese single-character words, including 天, meaning sky, 日, meaning sun, 水, meaning water, 田, meaning fields, 火, meaning fire, 星, meaning stars, and 你, meaning you. These words were selected, as they are commonly used in Chinese kindergarten children's daily conversations, and commonly seen in popular story and reference books for kindergartens and elementary schools. The commonality of these words had been confirmed by four independent kindergarten teachers, before being used in the present study.

Each word was read twice to children, who were then encouraged to write down the words. A scoring scheme was developed based on a Chinese character coding criteria used in previous research (Guan, Perfetti & Meng, 2015). Specifically, children's writing was scored according to its local and global conformity: Local conformity referred to the basic stroke-form correctness, whereas global conformity referred to the overall shape and configuration correctness. Based on its accuracy and integration, children could get up to 2 points for each word. One maximum point was allocated to local conformity, whereas another maximum point was allocated to global conformity. With respect to local conformity, if children wrote a four-stroke character (e.g., 日) with three correctly produced strokes (e.g., 口), they would be awarded a score of .75 (three correct strokes out of four) for that character. With respect to global conformity, one point was awarded when the character was recognizable as the correct Chinese character. Zero point was allotted when either the Chinese character was unrecognizable, or when no attempt was made to write the character. For example, the child might have written a character incorrectly (e.g., a written word comprising of two incorrectly produced strokes, 火) but it could still be legible as the correct character (i.e., 火). Two research assistants scored the writing of each child. The inter-rater reliability was. 94.

Results

Table 1 shows the means and standard deviations of and correlations among all variables. As expected, VMI and EF were positively correlated with Chinese word reading (rs = .30 and .17, ps < .05) and writing (rs = .31 and .16, ps < .05). Child gender (0 = boy; 1 = girl) and age were positively correlated with reading (rs = .13 and .20, ps < .05) and writing (rs = .14 and .29, ps < .05) abilities. Maternal education (i.e., family socioeconomic status) was positively correlated with reading

Table 1 Means (M) and standard deviations (SD) of and correlations among variables

			Correlations							
Variables	*M*	*SD*	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1. Gender	–	–	–							
2. Age	57.99	4.77	.04	–						
3. Maternal education	3.05	1.14	.19**	.01	–					
4. Rapid automatized naming	24.61	8.69	–.14**	− .11*	-.27**	–				
5. Executive functioning	− 0.01	0.76	.07	.02	.10†	− .10*	–			
6. Visuomotor integration	16.95	2.08	.21**	.21**	.18**	− .26**	.03	–		
7. Chinese word reading	31.55	15.55	.13**	.20**	.34**	− .57**	.17**	.30**	–	
8. Chinese word writing	5.73	3.19	.14**	.29**	.36**	− .48**	.16**	.31**	.68**	–

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

($r = .34$, $p < .01$) and writing ($r = .36$, $p < .01$) abilities. In fact, it was also positively correlated with VMI ($r = .18$, $p < .01$) and, at a trend level, EF ($r = .10$, $p = .05$), and negatively correlated with RAN ($r = -.27$, $p < .01$). Finally, RAN was negatively correlated with reading ($r = -.57$, $p < .01$) and writing ($r = -.47$, $p < .01$) abilities.

Hierarchical regression analyses were conducted separately for Chinese word reading and writing. Predictor variables were entered based on both theoretical and statistical considerations. Child gender and age and maternal education were entered in Step 1 to control for potentially confounding background factors. RAN was entered in Step 2 to test whether VMI and EF (i.e., domain-general abilities) explained unique variance in Chinese word reading and writing, above and beyond RAN (i.e., domain-specific abilities). To examine the unique roles and relative importance of VMI and EF in understanding Chinese word reading and writing, the remaining steps were conducted twice, once with EF being entered in Step 3 and VMI being entered in Step 4, and once with the two predictor variables being entered in the reversed order. Table 2 shows the standardized coefficients.

When child and family background variables (i.e., child gender and age and maternal education) were entered in Step 1, they explained 16 and 22% of the variance in Chinese word reading and writing, respectively. Even controlling for these background variables, in Step 2, RAN still accounted for 23 and 13% unique variance in Chinese word reading and writing, respectively. In Step 3, EF and VMI each accounted for 1% unique variance in Chinese word reading and in Chinese word writing, above and beyond family background variables and RAN. When controlling for each other, EF and VMI remained significant, as indicated by Step 4: EF and VMI each explained 1% additional variance in Chinese word reading and writing. In other words, children with better EF, or with better VMI, were better able to read and write Chinese characters.

Table 2 Hierarchical regression models of Chinese word reading and Chinese word writing

		Chinese word reading				Chinese word writing			
		R^2	ΔR^2	β	*t* value	*R*	R^2	β	*t* value
Step 1	Gender	.16	.16**	.06	1.26	.22	.22**	.06	1.33
	Age			.20	4.07**			.29	6.09**
	Maternal education			.33	6.53**			.35	7.20**
Step 2	Rapid automatized naming	.39	.23**	− .50	− 11.38**	.35	.13**	− .38	− 8.38**
Step 3	Executive functioning	.40	.01*	.10	2.37*	.36	.01*	.09	2.01*
Step 4	Visuomotor integration	.41	.01**	.12	2.65**	.37	.01**	.13	2.77**
Step 3	Visuomotor integration	.40	.01*	.12	2.60*	.36	.01**	.13	2.74**
Step 4	Executive functioning	.41	.01*	.10	2.41*	.37	.01*	.09	2.06*

Regression analysis was conducted twice for each outcome variable, once with executive functioning being entered in Step 3 and visuomotor integration being entered in Step 4, and once with the two predictor variables being entered in the reversed order, to examine the unique variance explained by each predictor variable

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

Discussion

The present study examined whether VMI and EF were uniquely linked to Chinese literacy skills in second-year kindergarten children from Hong Kong. To our best knowledge, it was the first study to simultaneously test VMI and EF as correlates of Chinese word reading and writing. Consistent with our hypotheses, VMI and EF each explained unique variance in both Chinese word reading and writing, above and beyond the contributions of child age, gender, RAN and maternal education. Perhaps more importantly, even controlling for each other, VMI and EF remained significant correlates of Chinese word reading and writing, suggesting that VMI and EF may constitute critical, domain-general processes that support the development of reading and writing in nonalphabetic languages, such as Chinese.

VMI and EF were unique correlates of Chinese word reading and writing

Consistent with prior research linking VMI to word reading and writing in English (Becker et al., 2014; Cameron et al., 2012) and word writing in simplified Chinese scripts (Wang et al., 2014, 2015), our results indicated that VMI was uniquely linked to word reading and writing in traditional Chinese scripts, even controlling for child and family background variables, RAN, and EF. Because of the logographic and morphosyllabic nature of the Chinese writing system, Chinese characters, particularly those in traditional scripts, are characterized by complex visual structures and diverse spatial configurations (Kao, 2000; Shu et al., 2006). Chinese characters consist of multifaceted units, such as strokes, subcomponents, radicals, and phonetics, that are arranged in many different ways. Some commonly used Chinese characters also look very similar. The addition of one stroke, or even the slight alternation of its spatial orientation, can completely change the sound and meaning of a character. Therefore, in order to read and write efficiently in Chinese, children have to utilize their VMI skills to quickly recognize the shapes of individual characters and distinguish between visually similar words. VMI may further contribute to Chinese word reading and writing by facilitating information transfer across modalities (Sigrist et al., 2013; Zmigrod & Hommel, 2013), which may be invoked when children map the visual-orthographic characteristics of specific characters onto the auditory-phonological ones, and when children reproduce Chinese words through verbal articulation (in the case of reading aloud) or fine motor movements (in the case of writing). More generally, our work extended existing literature by highlighting the importance of VMI in Chinese word reading and writing, a topic that had been underexplored in kindergarten children before.

Consistent with previous findings indicating that EF was associated with English word reading and spelling (Berlin & Bohlin, 2002; Blair & Razza, 2007; Dilworth-Bart, 2012; Ponitz et al., 2009) and Chinese word reading (Chung & McBride-Chang, 2011; Lan et al., 2011), our results indicated that EF was also an important correlate of Chinese word reading and writing. Considering the cognitive demands of reading and writing Chinese words, effective deployment of EF skills may promote children's literacy development by enhancing their capacities to store relevant information, suppress irrelevant information, and select and switch between alternative behavioural responses. As Chinese characters are visually complex, have complicated orthographic rules, and entail relatively opaque print-to-sound correspondences (Kao, 2006; Shu et al., 2003), children may require multiple EF skills, including working memory, inhibition control, and cognitive flexibility, to differentiate among similar looking and similar sounding characters and to translate their prints into correct sounds. EF may be particularly important in Chinese word reading and writing in Hong Kong, where traditional Chinese scripts (which are visually more complex than simplified Chinese scripts) are used and Cantonese (which is tonologically more complex than Mandarin) is spoken. It is worth noting that, as documented in some prior studies (Monn, Narayan, Kalstabakken, Schubert & Masten, 2017; Yeniad et al., 2014), EF was *not* significantly correlated with child age in our data, possibly due to the fact that we only included second-year kindergarten children, which limited the variance and thus correlability of child age, and that EF has an exceptionally long maturation schedule that continues into adolescence and even early adulthood (Blakemore & Choudhury, 2006; Diamond, 2013; Garon et al., 2008). However, combined with our findings on VMI, our study demonstrated that reading and writing in Chinese, like in English (Blair, 2016; Cameron et al., 2016; De Franchis et al., 2017), may involve domain-general skills, such as VMI and EF, as well as domain-specific skills, such as those potentially captured by RAN, as elaborated below.

Although not the primary goal of this study, RAN was correlated with Chinese word reading and writing, a finding well-documented in prior work on learning Chinese and English words (Chung, 2015; Shu et al., 2006). As summarized by other researchers (Bowers & Newby-Clark, 2002; Georgiou et al., 2012; Norton & Wolf, 2012), RAN is likely to reflect multiple processes crucial for language production, including activation of the mental lexicon, retrieval of visual-orthographic and auditory-phonological information, and integration of multiple sources of information to support semantic and syntactic processing. Since Chinese characters have relatively arbitrary linkages between shapes and sounds (Kao, 2006; Shu et al., 2003), the abilities to quickly and accurately process different sources of visual, phonological, and orthographic information, integrate them to form a coherent mental representation of each digit or word, and respond by reading aloud may be important in children's reading and writing. Notably, RAN was also correlated with VMI and EF, suggesting that the naming of digits or words may also rely on VMI (which is facilitative of information transfer across modalities; Sigrist et al., 2013; Zmigrod & Hommel, 2013) and EF (which involves the ability to hold and manipulate mental representations in working memory; Blair, 2016; Diamond, 2013). Future research should be directed at examining the interrelationships among RAN, VMI, and EF.

Limitations and conclusions

This study had several limitations. First, although our sample was diverse in family socioeconomic status, it only included second-year kindergarten children, which limited the generalizability of our findings. Further studies should include children of different ages to test whether VMI and EF are uniquely linked to Chinese word reading and writing at different developmental stages. Relatedly, considering that the three subcomponents EF tend to be more differentiated and specialized with age (Lee et al., 2013; Miyake & Friedman, 2012; Willoughby et al., 2012), the inclusion of older children in further studies may allow for an examination of whether working memory, inhibitory control, and cognitive flexibility are uniquely linked to Chinese literacy skills. Another issue pertaining to generalizability is that we only included children from Hong Kong. In Lan et al. (2011) cross-cultural study, EF was more strongly correlated with Chinese word reading (in Chinese kindergarten children) than with English word reading (in American kindergarten children). Additional research based on children from different countries, and from different regions of China, is needed to test if EF is more strongly associated with reading and writing in one language than another, and in traditional Chinese scripts than in simplified Chinese scripts, respectively.

Second, due to time constraints, we were only able to use one measure in the child test session to indicate each domain-general cognitive process. Emerging research, however, suggests that VMI and EF may be best operationalized by a wide range of measures (Decker et al., 2011; Diamond, 2013). Therefore, future researchers should use multiple indices of VMI, such as the *spontaneous* copying task in the Beery-Buktenica Developmental Test of Visual-Motor Integration (Beery et al., 1997) and the *delayed* copying task in the Bender Visual-Motor Gestalt Test (Brannigan & Decker, 2003), as well as multiple indices of EF, such as the Hearts-And-Flowers Task (Calderon et al., 2014; Davidson et al., 2006), Pencil Tap Test (Nigg, 2000), Dimensional Change Card Sort (Zelazo et al., 2003), and Head-Toes-Knees-Shoulders Task (Chung, 2015), to depict a more comprehensive picture on how domain-general skills may contribute to the development of Chinese word reading and writing.

Third, though significant, the bivariate correlations of VMI and EF with Chinese word reading and writing were modest in strength. In fact, in our multivariate analysis, VMI and EF each explained only 1% unique variance in the two outcome measures, suggesting that they may only be two of the many cognitive processes that are required for efficient reading and writing (Cameron et al., 2016; De Franchis et al., 2017). An important direction for future research is to move from the testing of different cognitive processes as independent correlates towards the building of a comprehensive model which explains how these processes are integrated, as a whole, to support reading and writing. Finally, the cross-sectional design of our study precluded conclusive claims about causation. Longitudinal studies are needed to disentangle the temporal order of the relationships between VMI, EF, and Chinese word reading and writing.

Despite these limitations, our focus on a non-alphabetic language, examination of VMI and EF as independent correlates, and inclusion of strong controls provided important insights to the literature on early word reading and writing. Theoretically, our findings highlighted the unique roles of VMI and EF in supporting Chinese word reading and writing in early years. Chinese word reading and writing are both visually complex and cognitively demanding. To master such skills, domain-general skills may be required to coordinate different domain-specific skills, such as by linking the visual-orthographic and auditory-phonological information associated with different characters, directing attention to relevant information and suppressing irrelevant one, and reproducing words through verbal articulation or motor movements. Practically, our findings pointed to the utility of targeting VMI and EF to help kindergarten children to learn to read and write Chinese characters. If VMI and EF, as malleable qualities (Decker et al., 2011; Diamond, 2013), really constitute the building blocks for reading and writing in Chinese, parents and teachers may use such activities as tracing objects, making crafts, and jigsaw puzzles to enhance the VMI skills of kindergarten children (Decker et al., 2011). They may also use such games as "Simon Says," "Red Light, Purple Light," and "Color-Matching Freeze" to improve children's EF (Tominey & McClelland, 2011). Interventions targeting kindergarten children's literacy achievement, or academic success in general, should consider incorporating some VMI- and EF-related activities in their programmes.

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