Linguistic Influences on Mathematics Learning: The Relations between Spacing/Spatial Relationship in Handwriting Legibility, Visual-Motor Integration (VMI), and Number Line Estimation

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Previous studies have uncovered the relationship between handwriting and mathematics performance, without articulating the underlying cognitive mechanism. With 197 Chinese fourth graders as participants, this study explored the mechanism by which the spacing/spatial relationship in handwriting legibility affects number-line estimation through VMI. The results indicate that (1) the spacing/spatial relationship in handwriting legibility had a direct and positive effect on students' number-line estimation performance; (2) VMI completely mediated the relationship between the spacing/spatial relationship in handwriting legibility and number-line estimation. Overall, the findings confirmed one specific mechanism of linguistic influences on students' numerical knowledge. Possible explanations for the results and implications for future research are discussed.

Handwriting, as one basic language skill (Kao, 1995), has been uncovered to be closely related to students' mathematics performance (e.g., Li & Nuttall, 2001; Rodic et al., 2015). However, little work has investigated the cognitive mechanism by which the relation between handwriting and mathematics performance emerges. Handwriting legibility, representing the construction, accuracy, or quality of the handwriting products (Maeland, 1992; Shen et al., 2012; Tseng, 1993), is typically operationalised as the spatial consistency of the handwriting products (Bo, 2014), including but not limited to indicators like the letter or character (and stroke/radical)'s spacing/spatial relationship, formation, size, and slope, etc. (e.g., Bumin & Kavak, 2008; Maeland, 1992). These spatial-oriented properties (Bo, 2014) imply that development in handwriting legibility may, to some extent, predict students' spatial advancement (e.g., Abou-El-Saad et al., 2017; Cheng-Lai et al., 2013; Li et al., 1999a, 1999b; Mealand, 1992; Kao, 1999, 2000). Combined with the identified promotion effect of spatial cognition on students' mathematics performance (see a meta-analysis by Xie et al., 2020), extant research comprehensively depicts an intermediary logic to construct the general relationship between handwriting and mathematics performance with the help of spatial cognition. Particularly, VMI, as one critical component of spatial skills (Xie et al., 2020), has been demonstrated to share a high coincidence in cognitive processing needs with handwriting legibility (Weil & Amundson,1994), necessitating the dynamic integration of perceptual, cognitive, and motor components (Kao, 1999, 200) and viewing copying geometric shapes as skill essentials. Previous studies on handwriting identified a significant link between the spacing/spatial relationship in handwriting legibility and VMI (e.g., Parush et al., 2010; Tseng & Murray, 1994). Furthermore, number line estimation was discovered to operate as a spatially meaningful numerical representation for mathematics (Gunderson et al., 2012). As Dowker and Nuerk (2017) suggested, "so far, much research about linguistic influences on numerical cognition has simply demonstrated that language influences number without investigating the level at which a particular language influence operates" (p. 3). In this context, focused on the spacing/spatial relationship in handwriting legibility, a specific cognitive pathway in which spacing/spatial relationship plays a crucial role in the development of number line estimation by helping youngsters to develop a superior VMI ability was hypothesised in this study. In specific with a focus on Chinese characters, the current research aims to (1) quantify the relationship between spacing/spatial relationship in handwriting legibility, VMI, and number

line estimation; and (2) explore whether VMI plays a mediating role in the spacing/spatial relationship in handwriting legibility and students' number line estimation performance. These efforts may contribute to the field by deepening the understanding of the linguistic influences on numerical cognition, meanwhile providing empirical evidence about one specific mechanism in which how components in linguistic, spatial, and mathematics domains interact with each other.

Theoretical Framework

General intelligence theory (Spearman, 1904) demonstrates that there is a general intelligence factor out of human's different cognitive abilities (e.g., language, and mathematics) (Spearman, 1904). Sociocultural theory claims that language and thought evolve together, with linguistic experience driving the formation of concepts. Similarly, social constructivism (Ernest, 1991) views mathematics as a social construction, and linguistic knowledge acts as the basis of mathematical knowledge. From the broad concept of language, those theories underline the significance of language to mathematics and the inherent relationship between the two (Lu et al., 2022).

On this basis, focusing on the "visuospatial-orthographic" level of Dowker and Nuerk (2017)'s linguistic framework, narrowing to handwriting aspect, the psycho-geometric theory of Chinese-character writing postulated that the psycho-geometric pattern of the visual-spatial configuration of Chinese characters serves as a critical foundation for cognitive change (Kao, 2000). Chinese-character writing, according to Kao, is a dynamic integration of the writer' perception, cognition, and action, as well as a re-training and enhancement of the writer's visuospatial ability. This theory establishes the promotion effect of logographic character writing in students' spatial perception, representation, and imagination, thereby laying the groundwork for explaining the development of students' spatial cognition and, consequently, mathematics performances in the perspective of linguistics. In this sense, a general mediation framework involving spatial cognition is proposed here to claim the positive influence of handwriting on youngsters' mathematics performance. Further, combined with the conceptual basis clarified earlier, this study postulates a refined theoretical framework concerning spacing/spatial relationship in handwriting legibility, VMI, and number line estimation.
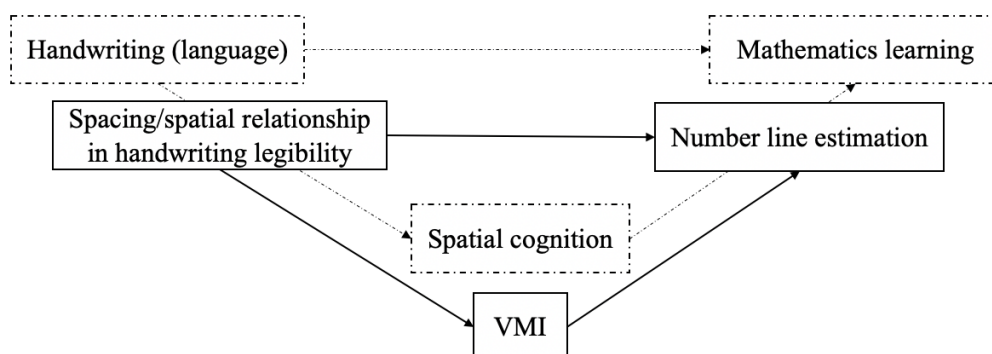

Figure 1. The theoretical framework of the present study.

Method

Participants and Procedures

Participants are 202 fourth graders from one mainstream primary school in central China. Five students did not participate in the handwriting task and were excluded from the analysis.

The final sample included 104 (52.79%) male students and 93 (47.21%) female students, with the mean age being 9.37 years.

Students were asked to complete a variety of paper-pencil tasks, including handwriting, VMI, and number-line estimation (See some sample tasks in Figure 2). Students were assigned tasks in their classrooms (one class at a time). The handwriting task required students to copy a 9*10-Chinese character template (All of the characters were chosen based on the Chinese characters' six main basic structural forms, and 25 out of the 30 basic stroke units, ensuring their representativeness; Li-Tsang et al., 2011) as accurately as possible in 4 minutes. The VMI required students to duplicate 24 line drawings of specified geometric designs (Beery & Beery, 2010). The number line estimation comprised 22 problems involving the numbers 0-1000, in which participants needed to determine the location of a target number on a blank number line, and the error between the target number's actual position and the participant's estimate reflected the participants' internal mental number line representation. The VMI and number line estimation tasks consisted of two phases, i.e., the practice and the experimental phases. In both phases, the invigilator (the first author) supplied detailed response instructions (see Booth & Siegler, 2006 for details). Two more teachers were assigned to manage class discipline and ensure that participants provided careful responses.

Where would you put 158 ?

0   1000

Figure 2. Sample characters/forms/items in the Chinese handwriting, VMI, and number line estimation tasks.

A five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) was used to assess students' performance in spacing/spatial relationship in handwriting legibility (the four-item scale includes the following: 1. Correct spacing between strokes/radicals, the correct position of components; 2. Regular spaces between characters; 3. The alignment of the lines of writing; 4. Square configuration/baseline orientation: no characters are out of grid/line, nor do characters overshoot/undershoot the baseline; with appropriate margins). The first author conducted the handwriting evaluation with participants' identities and performances in other tasks blinded. The VMI evaluation was conducted by a group of undergraduates recruited from one college in XX province in China, with the test manual followed strictly (Beery& Beery, 2010). The number line estimate performance was graded using the criteria provided by Rittle-Johnson et al. (2001). Discrepancies during all the rating procedures were resolved by double reviews of original criteria. The reliability and validity of all instruments are good.

Data Analysis

According to the theoretical model, data analysis in this study included three steps. Firstly, descriptive and correlational statistics on variables of interest were computed. Then, confirmatory factor analysis (CFA) was utilised to validate the psychometric qualities of items within spacing/spatial relationship in handwriting legibility. Lastly, structural equation modelling was formulated to assess the effects of the independent latent variable on the dependent explicit variable, following the mediation effect examination to determine the

influence of VMI on the effects of spacing/spatial relationship in handwriting legibility on number-line estimation.

Results

Descriptive and Correlational Statistics

Table 1 shows the correlation among variables. Results indicated that spacing/spatial relationship in handwriting legibility, VMI, and number line estimation were significantly and positively correlated with each other.

Table 1

Mean, Standard Deviations, and Correlations among Variables

Variable	Correlation		
	1	2	3
1 h	1		
2 vmi	.598**	1	
3 nl	.205**	.275**	1
Mean	4.050	17.210	14.360
Standard deviation	.667	2.958	3.768

Note. All correlation coefficients are statistically significant at the $p < 0.01$ level. *h* = spacing/spatial relationship in handwriting, vmi = VMI, nl = number-line estimation (the same as follows).

Structural Equation Modelling Analysis

CFA was first employed to estimate the measurement properties of the handwriting legibility subscale: $\chi^2 = 2.268$, $df = 2$, $p = 0.322$, RMSEA = 0.026, CFI = 0.999, TLI = 0.997, SRMR = 0.015, and the factor loadings were acceptable (Figure 3).
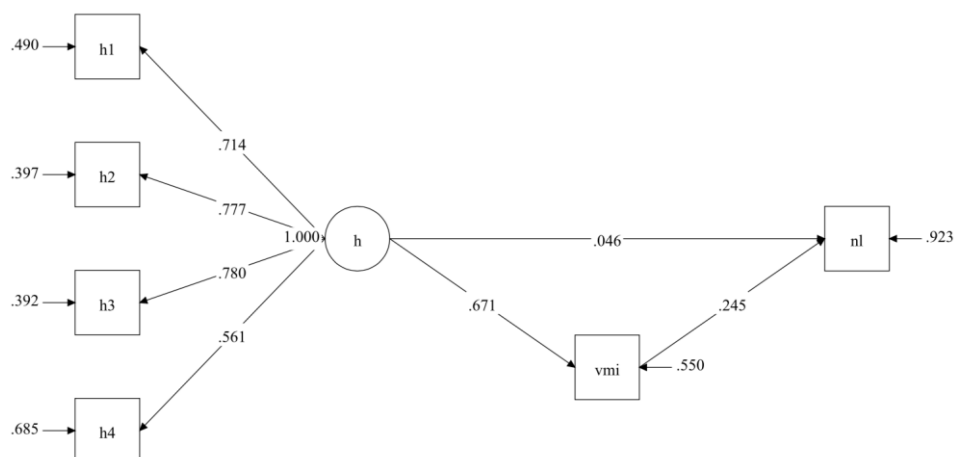

Figure 3. The structural equation model exploring the relationship between spacing/spatial relationship in handwriting legibility, VMI, and number-line estimation.

On this basis, structural equation modelling was further analysed, and the standardised path coefficients of the model were depicted in Figure 3. The model fitted the data adequately with $\chi^2 = 16.329$, $df = 8$, $p = 0.038$, CFI = 0.976, TLI = 0.956, RMSEA = 0.073, SRMR = 0.032. Besides, the model showed that spacing/spatial relationship in handwriting legibility positively

predicted VMI and number-line estimation; VMI positively predicted number-line estimation. In further analysis of the mediation effect of VMI, bootstrapping processes were employed to obtain a 95% confidence interval with the original data resampled and replaced 1000 times. The results (Table 2) did not include zero, indicating a significant mediation effect ($p = 0.011$).

Table 2
Results of the Bias-Corrected Bootstrap Test

Paths	Standardised β	SE	Bias-corrected 95%CI	
			Low	High
h→vmi→nl	.164*	.065	.045	.300

*$p < 0.05$.

Discussion and Implications

Based on the general relationship between handwriting, spatial cognition, and mathematics performance, this study modelled one specific mechanism interweaving spacing/spatial relationship in handwriting legibility, VMI, and number line estimation. Meanwhile, our findings confirmed the positive and close relationship between involved variables, as well as the significant mediation effect of VMI in this relationship. Those findings fit well with the psycho-geometric theory of Chinese-character writing, and the basic ideas elaborated by general intelligence theory, sociocultural theory, and social constructivism.

Going beyond previous findings demonstrating the relationship between handwriting and spatial cognition, or handwriting and mathematics performance, the present study not only identified the more specific variables (i.e., spacing/spatial relationship in handwriting legibility, VMI, and number line estimation, respectively) out of these domains but further uncovered a coherent mechanism of spacing/spatial relationship in handwriting legibility on VMI, then in turn, on number line estimation. The positive and close relationship between spacing/spatial relationship in handwriting legibility, VMI, and number line estimation highlights that common cognitive processing needs—spatial thinking, underlies those different domains. This finding supports existing findings by Kao (1999, 2000), Li and Nuttall (2001), and others, by confirming the unique visuospatial properties embedded in Chinese characters and the sound spatial experience accumulated by legible handwriting practice; meanwhile, it emphasised the spatial-numerical association underpinning numerical knowledge (Schneider et al., 2009), fitting well with Dehaene et al.'s (1993) claim that there exists an analogical representation of magnitude using the left-to-right spatial arrangement in the human's mental world. Besides, the significant correlation between spatial ability and numerical ability identified in Xie et al. (2020) ($r = 0.22$, p < 0.001) also lends considerable support to the current study.

Moreover, this study demonstrates a substantial relationship between spacing/spatial relationship in handwriting legibility and VMI, which is stronger than earlier research concentrating on handwriting legibility and VMI (e.g., Bumin & Kavak, 2010; Hellinckx et al., 2013; Klein et al., 2011; Preminger, 2004; Wicki, 2014). Focusing on the more specific aspect of handwriting legibility may provide plausible explanations for this disparity. According to the characterisation of the present handwriting evaluation scale, as one critical indicator of handwriting legibility, spacing/spatial relationship encompasses highly spatial-orientated properties at both analytic (stroke/radical) and holistic (character) levels (Lam et al., 2011), such as the position/spacing of/between strokes/radicals/characters, alignment of characters, attention on the grid, etc. (e.g., Gilboa, 2014; Jameel, 2017; Klein et al., 2011; Parush, 2010; Linda et al., 2014). These profoundly spatial features are much in line with the visuospatial essence of VMI ability, suggesting the key role of spacing/spatial relationship in handwriting

legibility. In addition, the script inconsistency relative to earlier studies might partially account for the present high correlation. As numerous studies (e.g., Kao, 1995, 2000; Lai, 2008) suggested, compared with the linear arrangement of alphabetic letters, Chinese characters are featured as planar structure; occupying two-dimensional space in height and width, Chinese characters are logographic in nature and has high visual-spatial properties. As such, Chinese handwriting processes, in comparison to alphabetic ones, would entail a more systematic integration of the writer's perception, cognition, and motor (Kao, 2000), which corresponds better to the cognitive processes of VMI. This finding furthers the literature by identifying a more nuanced link between Chinese handwriting legibility and VMI, so providing new evidence on their homogeneity proposed in previous studies (e.g., Li et al., 2018).

Moreover, the complete mediation effect of VMI obtained currently indicates that the effect of spacing/spatial relationship in handwriting legibility on number line estimation is indirect. In other words, Chinese handwriting practice emphasising appropriate spatial positions of each stroke/radical/character in reference to the square frame and its spatial relationships with others, would firstly near-transfer as students' sharpened VMI ability, then, in turn, far-transfer as development in number line estimation performance. This indirectness is expected for language (handwriting) and mathematics source from two relatively different fields, and they need some bridge to construct the linkage. This study verified that VMI performed this role appropriately. Based on the prior knowledge on the linkage between handwriting and mathematics, and the unique visual-spatial properties of Chinese characters, this study adds to the literature with the identification of spatial thinking underlying handwriting legibility and its linkage with VMI and number line estimation. These findings establish a theoretical and empirical foundation for future research on domain-specific cognitive processes associated with language and mathematics learning, as well as provide practical implications for teachers regarding how to enhance students' numerical knowledge through spatial-related handwriting practice.

Notably, while the current work focuses on the fundamental mathematics skill of number line estimation, it is constrained in its exploration of the mechanisms underlying more complicated mathematics learning processes. Indeed, this impact is possible. Previous work has indicated that geometric ability requires a variety of spatial factors, including identifying the characteristics and interconnections of lines, angles, and shapes (Ünlü & Ertekin, 2017), and geometric problems are frequently constructed by figures, all of which are strongly linked to visualisation analysis; logical reasoning problem solving also demands a high level of spatial ability, including the capacity to create visual representations, mental transformations, and visualization, etc. (e.g., Hegarty & Kozhevnikov, 1999; Oostermeijer et al., 2014). Thus, both geometric and logical reasoning problems might have a stronger link with spatial abilities (or VMI in this study) than numerical abilities (Xie et al., 2020). Alternately, according to Geary et al. (2017) and Lin (2011), numerical ability serves as a foundation for the development of arithmetic and facilitates the acquisition of more advanced mathematical competencies, hence it's reasonable to speculate that spatial thinking pervades the whole mathematics field. Future research should integrate more mathematics domains and explore their relative strengths with VMI and handwriting legibility. Moreover, utilising Chinese characters as the handwriting instrument makes this study limited in terms of logographic-alphabetic comparison. A robust body of research has found that compared with alphabetic handwriting, Chinese handwriting practices can contribute to the writers' superior VMI ability than their western counterparts (e.g., Cui et al., 2012; Lai & Frederick, 2012; Lim et al., 2015; Mao, 1995; Ng et al., 2015). In this regard, future research could advance the field by embracing this knowledge gap and conducting more empirical comparisons. Hopefully, this line of research can provide more opportunities for explaining the East-west disparities in mathematics success from the perspective of linguistics.

References

Abou-El-Saad, T., Afsah, O., Baz, H., & Shaaban, W. (2017). The relationship between visual-motor integration and handwriting skills in Arabic-speaking Egyptian children at the age of 4–6 years. *The Egyptian Journal of Otolaryngology, 33*(4), 663–669.

Beery, K. E. & Beery, N. A. (2010). *The Beery-Buktenica Developmental Test of Visual–Motor Integration with supplemental developmental tests of visual perception and motor coordination for children and adults with stepping stones age norms from Birth to Age 6, Administration, scoring, and teaching manual* (6th ed.). NCS Pearson.

Bo, J., Colbert, A., Lee, C. M., Schaffert, J., Oswald, K., & Neill, R. (2014). Examining the relationship between motor assessments and handwriting consistency in children with and without probable developmental coordination disorder. *Research in Developmental Disabilities, 35*(9), 2035–2043.

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology, 42*(1), 189–201.

Bumin, G., & Kavak, S. T. (2008). An investigation of the factors affecting handwriting performance in children with hemiplegic cerebral palsy. *Disability and Rehabilitation, 30*(18), 1374–1385.

Cheng-Lai, A., Li-Tsang, C. W., Chan, A. H., & Lo, A. G. (2013). Writing to dictation and handwriting performance among Chinese children with dyslexia: Relationships with orthographic knowledge and perceptual-motor skills. *Research in developmental disabilities, 34*(10), 3372–3383.

Cui, Y., Zhu, Y., Laukkanen, H., & Rabin, J. (2012). Evaluation of visual-motor integration skills in preschool and elementary school-aged Chinese children. *Journal of Behavioral Optometry, 23*(5-6), 123–128.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology General, 122*(3), 371–396.

Dowker, A., Nuerk, H-C. (Eds.). (2017). *Linguistic influences on mathematical cognition.* Frontiers Media.

Geary, D. C., Nicholas, A., Li, Y., & Sun, J. (2017). Developmental change in the influence of domain-general abilities and domain-specific knowledge on mathematics achievement: An eight-year longitudinal study. *Journal of Educational Psychology, 109*, 680–693.

Gilboa, Y., Josman, N., Fattal-Valevski, A., Toledano-Alhadef, H., & Rosenblum, S. (2014). Underlying mechanisms of writing difficulties among children with neurofibromatosis type 1. *Research in developmental disabilities, 35*(6), 1310–1316.

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: the role of the linear number line. *Developmental Psychology, 48*(5), 1229–1241.

Hegarty, M., & Kozhevnikov, M. (1999). Types of visual-spatial representations and mathematical problem solving. *Journal of Educational Psychology, 91*(4), 684–689.

Hellinckx, T., Roeyers, H., & Van Waelvelde, H. (2013). Predictors of handwriting in children with autism spectrum disorder. *Research in Autism Spectrum Disorders, 7*(1), 176–186.

Jameel, H. T., & Nabeel, T. (2017). Effect of visual motor integration training on legibility of urdu handwriting. *Pakistan Journal of Education, 34*(1), 81–94.

Kao, H. S. R. (1999). A psycho-geometric theory of Chinese character writing. In C. G. Leedham, M. Leung, V. Sagar, & X. Xuhong (Eds.), *Proceedings of the 9th biennial conference of the International Graphonomics Society*, Singapore.

Kao, H. S. R. (2000). *Chinese calligraphic therapy.* University of Hong Kong Press.

Kao, S. R., & Guan, Q. H. (1995).《書法與認知》, 台北市: 東大圖書公司.

Klein, S., Guiltner, V., Sollereder, P., & Cui, Y. (2011). Relationships between fine-motor, visual-motor, and visual perception scores and handwriting legibility and speed. *Physical & Occupational Therapy in Pediatrics, 31*(1), 103–114.

Lai, M. Y. (2008). An exploratory study into Chinese and English speaking children's visual perception and their spatial and geometric conceptions in Piagetian tasks. *HKU Theses Online (HKUTO).*

Lai, M. Y., & Leung, F. K. S. (2012). Visual perceptual abilities of Chinese-speaking and English-speaking children. *Perceptual and Motor Skills, 114*(2), 43–445.

Lam, S. S., Au, R. K., Leung, H. W., & Li-Tsang, C. W. (2011). Chinese handwriting performance of primary school children with dyslexia. *Research in Developmental Disabilities, 32*(5), 1745–1756.

Li-Tsang, C. W. P., Au, R. K. C., Chan, M. H. Y., Chan, L. W. L., Lau, G. M. T., Lo, T. K., et al. (2011). Handwriting characteristics among secondary students with and without physical disabilities: A study with a computerized tool. *Research in Developmental Disabilities, 32*, 207–216.

Li-Tsang, C. W., Au, R. K., Chan, M. H., Chan, L. W., Lau, G. M., Lo, T. K., & Leung, H. W. (2011). Handwriting characteristics among secondary students with and without physical disabilities: A study with a computerized tool. *Research in Developmental Disabilities, 32*(1), 207–216.

Li, C., & Nuttall, R. L. (2001). Writing Chinese and Mathematics Achievement: A Study with Chinese-American Undergraduates. *Mathematics Education Research Journal. 13*, 15–27.

Li, C., Nuttall, R. L., & Zhao, S. (1999b). The effect of writing Chinese characters on success on the water-level task. *Journal of Cross-cultural Psychology, 30*(1), 91–105.

Li, C., Nuttall, R. L., & Zhu, W. (1999a). Writing Chinese characters and success on Mental Rotation Test. *Perceptual and Motor Skills, 88*, 1261–1270.

Lim, C. Y., Tan, P. C., Koh, C., Koh, E., Guo, H., Yusoff, N. D., ... & Tan, T. (2015). Beery-Buktenica Developmental Test of Visual-Motor Integration (Beery-VMI): lessons from exploration of cultural variations in visual-motor integration performance of preschoolers. *Child: Care, Health and Development, 41*(2), 213–221.

Lin, C. (2011). 智力发展与数学学习 [*The development of intelligence and mathematical learning*] (4th ed.). Beijing: China Light Industry Press.

Linda, F. L., Thanapalan, K. C., & Chan, C. C. (2014). Visual-perceptual-kinesthetic inputs on influencing writing performances in children with handwriting difficulties. *Research in developmental disabilities, 35*(2), 340–347.

Lu, H., Leung, F. K., & Fan, Z. (2022). Chinese language and students' mathematics learning: a meta-analysis. *ZDM–Mathematics Education*. https:doi.org/10.1007/s11858-022-01333-x

Maeland, A. F. (1992). Handwriting and perceptual-motor skills in clumsy, dysgraphic, and 'normal' children. *Perceptual and Motor Skills, 75*(3_suppl), 1207–1217.

Mao, H. F. (1995) Performance of Chinese children in Taiwan on Beery's developmental test of visual motor integration. J*ournal of Occupational Therapy Association ROC, 13*, 13–24.

Ng, M., Chui, M., Lin, L., Fong, A., & Chan, D. (2015). Performance of the visual-motor integration of preschool children in Hong Kong. *Hong Kong Journal of Occupational Therapy, 25*, 7–14.

Oostermeijer, M., Boonen, A. J., & Jolles, J. (2014). The relation between children's constructive play activities, spatial ability, and mathematical word problem-solving performance: A mediation analysis in sixth-grade students. *Frontiers in Psychology, 5*, Article 782.

Parush, S., Lifshitz, N., Yochman, A., & Weintraub, N. (2010). Relationships between handwriting components and underlying perceptual-motor functions among students during copying and dictation tasks. *OTJR: Occupation, Participation and Health, 30*(1), 39–48.

Parush, S., Lifshitz, N., Yochman, A., & Weintraub, N. (2010). Relationships between handwriting components and underlying perceptual-motor functions among students during copying and dictation tasks. *OTJR: Occupation, Participation and Health, 30*(1), 39–48.

Preminger, F., Weiss, P. L., & Weintraub, N. (2004). Predicting occupational performance: Handwriting versus keyboarding. *The American Journal of Occupational Therapy, 58*(2), 193–201.

Rittle-Johnson, B., Siegler, R. S., & Alibali, M. W. (2001). Developing conceptual understanding and procedural skill in mathematics: An iterative process. *Journal of Educational Psychology, 93*(2), 346–362.

Rodic, M., Tikhomirova, T., Kolienko, T., Malykh, S., Bogdanova, O., Zueva, D. Y., Gynku, E. I., Wan, S., Zhou, X., & Kovas, Y. (2015). Spatial complexity of character-based writing systems and arithmetic in primary school: a longitudinal study. *Frontiers in Psychology, 6*, Article 333.

Schneider, M., Grabner, R. H., & Paetsch, J. (2009). Mental number line, number line estimation, and mathematical achievement: their interrelations in grades 5 and 6. *Journal of Educational Psychology, 101*(2), 359–372.

Shen, I. H., Lee, T. Y., & Chen, C. L. (2012). Handwriting performance and underlying factors in children with attention deficit hyperactivity disorder. *Research in Developmental Disabilities, 33*(4), 1301–1309.

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development, 75*(2), 428–444.

Spearman, C. (1904). "General intelligence", objectively determined and measured. *The American Journal of Psychology, 15*, 201–293.

Tseng, M. H. (1993). Factorial validity of the Tseng handwriting problem checklist. *Journal of Occupation Therapy Association ROC, 11*, 13–27.

Tseng, M. H., & Murray, E. A. (1994). Differences in perceptual-motor measures in children with good and poor handwriting. *The Occupational Therapy Journal of Research, 14*(1), 19–36.

Ünlü, M., & Ertekin, E. (2017). A structural equation model for factors affecting eighth graders' geometry achievement. *Kuram Ve Uygulamada Egitim Bilimleri, 17*(5), 1815–1846.

Weil, M. J., & Cunningham Amundson, S. J. (1994). Relationship between visuomotor and handwriting skills of children in kindergarten. *The American Journal of Occupational Therapy,48*(11), 982–988.

Wicki, W., Lichtsteiner, S. H., Geiger, A. S., & Müller, M. (2014). Handwriting fluency in children: Impacts and correlates. *European Journal of Psychology, 73*(2), 87–96. https://doi.org/10.1024/1421-0185/a000127

Xie, F., Zhang, L., Chen, X., & Xin, Z. (2020). Is spatial ability related to mathematical ability: A meta-analysis. *Educational Psychology Review, 32*(1), 113–155.