Current Psychology (2024) 43:8018–8028
https://doi.org/10.1007/s12144-023-05009-x

Hand copy performance of young children and the illiterate, semi-illiterate, and literate adults

Can Zhang[1] · Can Wang[1] · Zhiqing Deng[1] · Jie Gao[1] · Zilan Ding[2] · Juan Chen[1,3]

Accepted: 17 July 2023 / Published online: 24 July 2023

Abstract
Handwriting is essential for both children and adults. It is still unclear, however, how handwriting skills could be obtained. Here we tested the hand copy, the first step of handwriting, of children who started kindergarten for about one year (3–5 years old), who were in kindergarten for 2–3 years (5–6 years old), and who started elementary school for less than a year (6–7 years old). Participants were asked to copy down simple numbers and shapes under no time restraint. Their copy was also presented as visual feedback. In this case, their copy performance mainly reflects their abilities in visuomotor transformation. We found that the performance of children aged 5–6 years old was much better than that of the 3–5 years old ones, which could be due to the natural development of muscles and joints or the training at home or in kindergarten. We next tested illiterate, semi-illiterate, and literate adults with the same task to elucidate the contribution of natural development. Although illiterate adults had never been to school and could not read, they had well-developed and trained muscles and joints and had acquired fine motor skills during everyday life and work. Surprisingly, we found that the overall performance of the illiterate group was similar to that of the youngest (3–5 years old) children, which suggests that the visuomotor ability required for hand copy cannot be automatically obtained during growing up but requires specific training. Our findings provide new insights into visuomotor learning and have implications for handwriting interventions.

Keywords Writing · Development · Children · Illiterate adults

Introduction

Handwriting requires a combination of perceptual, motor, and cognitive skills (Fancher et al., 2018; Maldarelli et al., 2015). Children spend a considerable amount of time writing in school. For example, Marr et al. (Marr et al., 2003) found that children in kindergarten spend 42% of their school time on paper and pencil activities, and other studies reported that children spend 31–60% of their day writing and completing other fine-motor tasks (Van Waelvelde et al., 2012). Difficulties in handwriting negatively affect children's academic performance (Karlsdottir & Stefansson, 2002; Sandler et al., 1992). Therefore, the development of handwriting is vital to children's success in schools (Bo et al., 2014; Chang & Yu, 2005; Tseng & Hsueh, 1997; Wiley et al., 2016). Even for adults, handwriting plays a crucial role in everyday communication despite the ever-increasing use of keyboards for writing in our daily life. For example, people usually need to write letters or phone messages or fill out forms by hand.

Given the significant role of handwriting in children's development and adults' communication, one critical question is how handwriting skills could be obtained. As addressed above, handwriting is a complex perceptual-motor skill that includes visual perception, eye-hand coordination, visual-motor transformation, motor planning, and high-level cognitive skills such as memory and attention (Amundson, 1992; Cornhill & Case-Smith, 1996; Feder & Majnemer, 2007; Maeland, 1992). Children learn handwriting first through copying simple shapes or numbers while looking

✉ Juan Chen
juanchen@m.scnu.edu.cn

1 School of Psychology, Center for Studies of Psychological Application, Guangdong Key Laboratory of Mental Health and Cognitive Science, South China Normal University, Guangzhou, China

2 Psychological Science Department, Vassar College, Poughkeepsie, NY, USA

3 Philosophy and Social Science Laboratory of Reading and Development in Children and Adolescents (South China Normal University), Ministry of Education, Guangzhou, China

at these symbols. When the shapes and numbers are simple, their copying performance would mainly reflect their visuomotor ability (Beery & Buktenica, 1989). Can the visuomotor skills for handwriting be obtained through training in handwriting specifically? Can it be obtained through the transfer of learning motor skills in everyday life and work? These questions are, to a certain extent, related to a debate of whether or not children need specific training in handwriting. Some parents believe it is essential to learn writing as early as possible, while others believe that children can write well when they grow up with stronger muscles and flexible joints. In other words, specific training on writing is not required.

The debate above is related to the specificity and generalization of visuomotor learning (Fahle, 2005). If learning in one kind of motor skill cannot transfer to other motor skills, then we have to train each skill specifically. However, if learned skills could be generalized into other motor skills, then our learning efficiency would be greatly improved. Previous studies have been focusing on the specificity and transfer of perceptual learning (i.e., improvement of sensitivity in perception after extensive training) for decades (for review, see (Fahle, 2005)). Early studies found that perceptual learning has strong specificity, which means that the learning in one feature (such as orientation, spatial frequency) or position could not transfer to other features or positions (Ahissar & Hochstein, 1997; Crist et al., 1997; Irvine et al., 2000). However, recent studies have focused on how to enhance the generalization of perceptual learning (Wang et al., 2012; Xiao et al., 2008; Xiong et al., 2016; Zhang et al., 2010). For example, with a training-plus-exposure (TPE) procedure, perceptual learning of orientation can transfer entirely to an orthogonal orientation (Wang et al., 2012; Zhang et al., 2010).

With respect to motor learning, people have reported the specificity of visuomotor learning in speech (Tremblay et al., 2008), the direction of reaching (Yin et al., 2016), and tasks (sensorimotor adaptation vs. sequence learning) (Stark-Inbar et al., 2017) and have tested the generalization of motor skills across limbs(Lei & Wang, 2014; Nozaki et al., 2006; Yokoi et al., 2017). Letter or shape copying is the first step of handwriting and is a critical visuomotor skill for child development. What remains unclear, however, is whether or not the learning of visuomotor skills required for handwriting has specificity.

In the present study, we investigated the specificity of visuomotor learning in handwriting by asking participants to copy simple symbols (numbers or shapes) while looking at these symbols without a time limit. Visual feedback was given by presenting their own writing and the stimulus at the same time on the screen. The handwritings of young children (3–5, 5–6, and 6–7 years old) were compared to that of illiterate, semi-illiterate, and literate adults. The illiterate adults were healthy individuals and had well-developed muscles and joints but have never received formal education and cannot recognize any of the top 200 high-frequency Chinese characters (Cai & Brysbaert, 2010). All participants were able to work adequately and perform daily chores effectively when the study took place. If handwriting-related visuomotor skills do not require specific training, we would expect that illiterate adults were able to write the simple number and shapes properly. Otherwise, we would expect their performance to be close to that of the 3–5 years old children who haven't been to school yet.

Methods and Materials

Participants

A total of 105 participants took part in this study. There were three groups of children. Group 1 (*3–5 years old*) consisted of children between 3 and 5 years old who just started kindergarten (N = 21; 3.86 ± 0.39 years old, mean ± SD; 13 females; 8 males). Group 2 (*5–6 years old*) consisted of children who had been in kindergarten for about year (N = 27; 5.41 ± 0.50 years old, mean ± SD; 16 females; 11 males). Group 3 (*6–7 years old*) consisted of children in Grade one in elementary school (N = 28; 6.54 ± 0.51 years old, mean ± SD; 14 females; 14 males). The children participants were recruited via teachers in kindergartens or primary schools. To reach illiterate or semi-illiterate individuals, we utilized WeChat as a platform to post our flyers [to post our recruiting news]. Interested individuals who came across our recruitment news introduced potential participants to us.

There were also three groups of adults: illiterate adults (9 females; 1 male), semi-illiterate adults (8 females), and literate adults (3 females; 8 males). The criteria for illiterate participants are: (a) never received formal education; (b) cannot recognize any of the top 200 high-frequency Chinese characters. These participants did not attend school due to poverty or the false belief that school is unnecessary. The criteria for semi-illiterate participants are: (a) have received formal education for between 0–6 years; (b) can recognize 0–60 characters from the top 200 high-frequency Chinese characters list. The criteria for literate participants are: (a) have received more than 6 years of formal education; (b) can recognize more than 60 characters from the top 200 high-frequency Chinese characters list. For reading performance assessment, participants were provided with papers containing the top 200 high-frequency Chinese characters (Cai & Brysbaert, 2010), and were instructed to read each character one by one. The experimenter recorded the number of correctly read characters. None of the participants had a history of neurological or psychiatric disorders. All participants were able to work adequately and perform daily chores effectively when the study took place. The age, years of education, and reading performance are listed below in Table 1.

All participants had normal or corrected-to-normal vision and were right-handed as determined by their preferred hand to complete everyday activities, including using utensils.

Apparatus and stimuli

Stimuli were presented on a 14-inch laptop on a table (resolution: 1366 × 768, Lenovo). The experiment was programmed using the Psychtoolbox software package (Brainard & Vision, 1997; Pelli & Vision, 1997) (http://Psychtoolbox.org/); in MATLAB 2019 (The Mathworks, Natick MA; https://ww2.mathworks.cn/). Participants wrote on a Pen Tablet/Digitizer Tablet (size: 43 cm × 28.7 cm; WacomPTH-860) with a pen. The tablet recorded the writing trajectories, and the data were then exported and analyzed them with MATLAB 2019. Participants received real-time feedback of their handwriting on the screen (Fig. 1a).

Eight numbers (2, 3, 4, 5, 6, 7, 8, 9) and eight simple shapes (horizontal and vertical lines, cross, left and right arrows, circle, triangle, and square) were employed as stimuli (Fig. 1b). The stimuli were black and presented in the center of a white background in Arial font. The width of the stimuli was about 10 cm. These stimuli were chosen to examine the visuomotor skills of participants in handwriting because they were simple and commonly seen in everyday life, and therefore were familiar to all of our participants. Drawing the horizontal, vertical, and circle indicates one's fine movement control. Writing arrows and crosses tests an individual's ability to combine simple lines. Writing "2, 3, 4, 5, 6, 8, 9" tests the performance of writing curves and combinations of complex shapes. Writing "4" and "5" tests the ability to write a combination of lines and curves. Writing all the above symbols except the horizontal and vertical lines reflects the allocentric spatial ability of participants. Finally, writing circles, triangles, and squares would indicate an individual's ability to write closed shapes with different angles. All children participants were able to recognize these shape or numbers.

Procedure and design

Participants were asked to copy the stimulus presented on the screen to their digital tablet with the pen provided. At the beginning of each trial, participants were asked to hold the pen with their right hand to prepare for writing. A red fixation was shown for 500 ms, followed by a stimulus. They

Table 1 The age, years of education, and reading performance (i.e., the number of Chinese characters they could read) information of the three adults group

	Illiterate adults		Semi-literate adults		Literate adults	
	M	SD	M	SD	M	SD
Age	79.8	7.12	66	12.65	74.36	6.2
Education (Month)	0	0	5.25	11.79	122.18	30.62
Reading	0	0	24.375	20.22	88.27	17.64

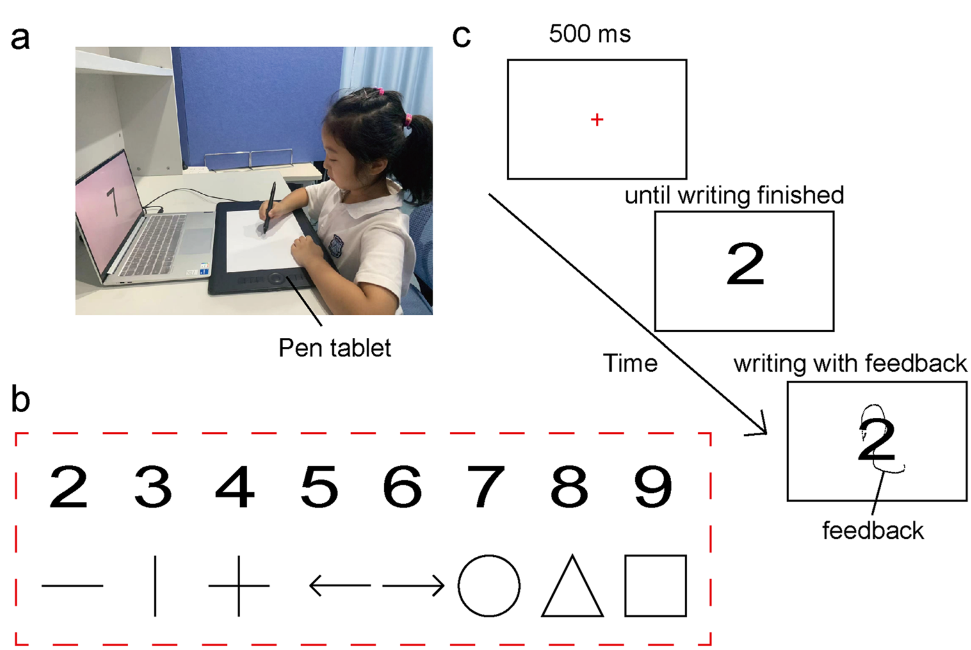

Fig. 1 The apparatus, stimuli, and protocol of the experiment. (**a**) Apparatus. Participants wrote on a Pen Tablet/Digitizer Tablet with a pen. The tablet recorded the writing trajectories. Informed consent was obtained from the girl's parents for publication of the girl's image in an online open-access publication. (**b**) The stimuli were numbers and simple shapes. (**c**) The protocol for each trial. Participants could see the number or shape while writing, and their writing was presented on the screen as visual feedback

could see the stimulus throughout the writing. Their handwriting was also shown on the screen in real-time, providing visual feedback of their performance. There was no time limit for each trial or the whole study. After the participant finished writing, the experimenter pushed a key to trigger the subsequent trial (Fig. 1c). If participants were not satisfied with their writing, they could ask to re-do the previous trial until they were satisfied with their performance. The result of that trial would be replaced by the new one. The order of the 16 stimuli was randomized.

To familiarize themselves with the procedure, each participant performed several practice trials before the actual experiment. It takes about 15 min to complete the study.

Data analysis

We examined the writing's glyph accuracy and error types for all groups of participants. Glyph accuracy refers to whether the participant's writing is consistent with the stimulus. The writing performance was first rated by two experimenters (i.e., the first two authors) independently. If their scoring were incongruent, a third experimenter (i.e., the last author) would provide her ratings. Ratings for individual were approved by all three experimenters. We categorized the handwriting performance as general correct, partially correct, and completely wrong. General correct means that the glyph corresponds to the stimulus. Partially correct means a part of the glyph corresponds to a component of the stimulus. Completely wrong means that the written result does not match the stimulus at all. Only the general correct trials were considered correct and were counted when calculating the accuracy. The error type analysis included the partial correct and completely wrong trials.

Chi-square tests were performed to test the main effects. All the statistical analyses were performed in Matlab (Mathworks, Natick MA; https://ww2.mathworks.cn/) and JASP (Love et al., 2019)(https://jasp-stats.org/). We also classified the participants' writing errors and analyzed the characteristics of the different error types.

Results

The performance of copying simple symbols reflects participants' visuomotor transformation ability. We first examined copy-writing in children and adult groups separately. We then compared the performance of children with that of illiterate adults to address whether or not the handwriting-related visuomotor transformation needs specific training or could be obtained through naturally grown-up (i.e., through the transfer of the learning in other visuomotor abilities during growing up).

Glyph accuracy

We first compared the glyph accuracy of children who had just started kindergarten (3–5 years old), who had been attending kindergarten for one year (5–6 years old), and children in the first grade (6–7 years old) with that of adults who were illiterate, semi-illiterate and literate (Fig. 2).

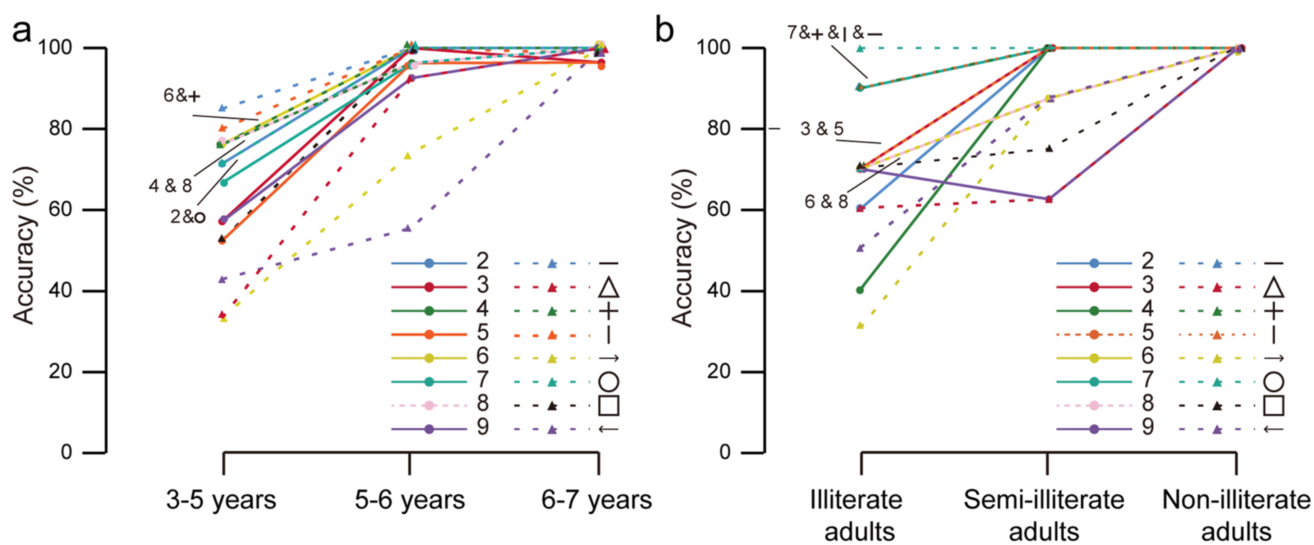

Fig. 2 The glyph accuracy of the three children groups (**a**) and the three adults groups (**b**). The accuracy was defined as the proportion of trials without any kind of errors

Glyph accuracy of children's groups

The accuracy was defined as the proportion of trials without errors (i.e., no missing or additive parts and the overall pattern is correct). Chi-square tests were carried out to assess the glyph performance of children with each glyph as a stratification factor.

There was a significant main effect of age on the accuracy for the children group ($p < 0.001$, Cohen's w = 0.36). With the increase of age, the accuracy also increased. The accuracy of the 3–5-years-old group in copying horizontal and vertical lines and circles was 85.71%, 80.95%, and 71.42%, respectively (Fig. 2a and Table S1). This result suggests that about 20% of children have difficulty in fine motor control at 3–5 years old. The common mistakes that lead to incorrect copying were either extra parts or 30 degrees over-tilted from a horizonal or vertical direction, or straight lines written in a zig-zag form; and the incorrect circle copies were not closed or looked like a square. The accuracy in copying horizontal and vertical lines and circles for the 5–6 and 6–7 age groups reached 100%.

There were significant differences in copying other figures between group 3–5 and 5–6: numbers 2 ($p = 0.004$), 3 ($p < 0.001$), 5 ($p < 0.001$), 6 ($p = 0.012$), 7 ($p = 0.015$), 9 ($p = 0.006$), vertical line ($p = 0.031$), cross ($p = 0.012$), triangle ($p < 0.001$), circle ($p = 0.004$), square ($p < 0.001$) and right arrow ($p = 0.008$). The 3–5 years old group wrote numbers 3, 5, 8, triangle, square, and left and right arrows with less than 60% accuracy. The 5–6-years-old group achieved over 90% accuracy in writing other symbols except for the left and right arrows.

The only significant difference between the writing of the 5–6 years old group and that of the 6–7 years old groups appeared in the writing of the left arrow ($p < 0.001$) and right arrow ($p = 0.004$), suggesting that the left and right arrows were the most difficult symbols to write for children. They either could not put the head of the arrow in the correct position relative to the horizontal line or showed partial mirror errors (See Fig. 3b, for example). The 6–7 years old group could write almost all symbols correctly except that one child wrote the left arrow as if a letter "F" (see Fig. 3c, sub69).

Overall, these results suggest that about 20% of children at 3–5 years old still show difficulty in fine motor control. Between one-third and two-thirds of them struggled with writing complex letters and shapes, including numbers, triangles, squares, and left and right arrows. Left and right arrows were the most difficult among the complex symbols. Several children at 5 to 6 years old struggled to write arrows correctly.

Glyph accuracy of illiterate, semi-illiterate, and literate groups

The same analysis was performed on the three adult groups. First, there was a significant main effect of literacy on the correct rate ($p < 0.001$, Cohen's w = 0.58). For horizontal and vertical lines and circles, the accuracy of illiterate adults in writing was 90%, 90%, and 100%, respectively, suggesting the fine motor control ability of the illiterate individuals was good (Fig. 2b).The accuracies of writing numbers 3,5 8, triangles, square, and left and right arrows of illiterate adults are all less than 60%.

Semi-illiterate adults had achieved 100% accuracy in writing 2, 3, 4, 5, 7, horizontal lines, crosses, vertical lines, and circles, but the accuracy was less than 80% for writing 9, triangles, and squares. Literate adults could write all stimuli correctly (for more results, see Table S2).

The statistical results support the main effect of literacy on handwriting. There were significant differences in writing 2 ($p = 0.012$), 3 ($p = 0.042$), 4 ($p = 0.001$), 5 ($p = 0.042$), left arrow ($p = 0.015$) and right arrow ($p = 0.001$) among the three groups. There were significant differences in writing 4 ($p = 0.013$), and right arrow ($p = 0.025$) between illiterate adults and semi-illiterate adults. There was a trend of significant differences in writing 9 ($p = 0.058$) and triangles ($p = 0.058$) between semi-illiterate and literate adults. Literate individuals wrote 9 better than semi-illiterate individuals. No other statistically reliable differences were observed.

It is important to note that although all the 8 semi-illiterate participants can read between 1–60 Chinese characters, 4 out of the 8 semi-illiterate participants we tested never attended school (see Fig. 3e for example, sub22). One of the other 5 semi-illiterate participants attended school for 3 days (Fig. 3e, sub12). Another one attended school for one night. The other two attended school for 6 months and 3 years, respectively. In other words, most of these semi-illiterate participants learned to read through observation or were taught by other people, but not in systematic school. The fact that they wrote better is probably because they learned the structure of these letters and shapes and how to write them in their everyday life.

Comparison between the glyph accuracy of children and illiterate adults

First, we compared the performance of 3–5 years old children and illiterate individuals. No statistically reliable differences were observed between these two groups ($p = 0.349$; Cohen's w = 0.4). Then, we compared the performance of children in the 5–6 years-old group and illiterate individuals. There were significant differences in writing 2 ($p = 0.003$), 3 ($p = 0.015$), 4 ($p = 0.001$), 6 ($p = 0.015$), triangle ($p = 0.035$), right arrow ($p = 0.023$) and squares ($p = 0.015$) between

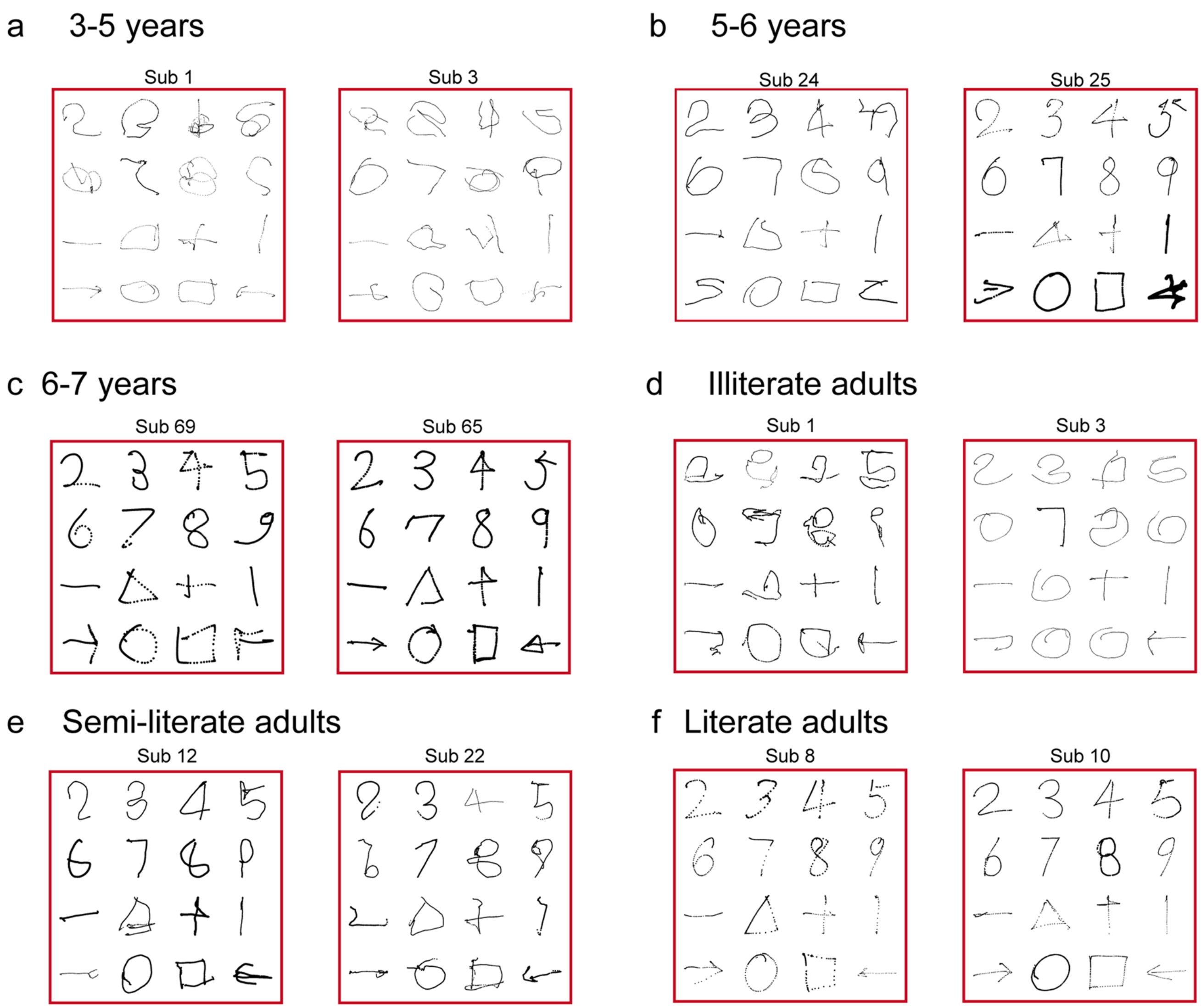

Fig. 3 Examples of writing from each children group and each adults group

these two groups. Generally, the writing of 5–6 years old children is more accurate than that of illiterate participants (for more results, see Table S3.) In other words, the writing of illiterate adults is close to that of the 3–5 years old children and less accurate than that of the 5–6 years old children.

Error types of children

The 3–5-years-old children showed the following errors: (a) Unable to draw straight horizontal or vertical lines (type 1); (b) Unable to copy down the provided symbol's structure (such as 2, 5, type 2); (c) Neglecting (missing) important component or adding additional components (such as write circles without closing it, type 3); (d) The relative position of the parts is wrong (type 4); (e) Mixing up triangles and squares, as they would often mistakenly draw a circle instead of a triangle or vice versa (type 5); (f) Complete or partial mirror writing (especially seen in copying down number 4, 6 and 9, type 6); (g) Wrong global orientation (for instance, writing 8 as two circles aligned horizontally, type 7)(Fig. 4a, Table 2). Children may make multiple errors in one symbol.

The 5–6 years old group did not show any type 1 errors (Table 2). They showed type 2 errors only in writing arrows. Some of them show types 4, 5, and 6 errors. The most difficult symbols for them to write were the arrows (Fig. 4b). The 6–7 years old children who have attended elementary school only show the mirror-writing error, and their mistakes were rarely seen (Fig. 4c).

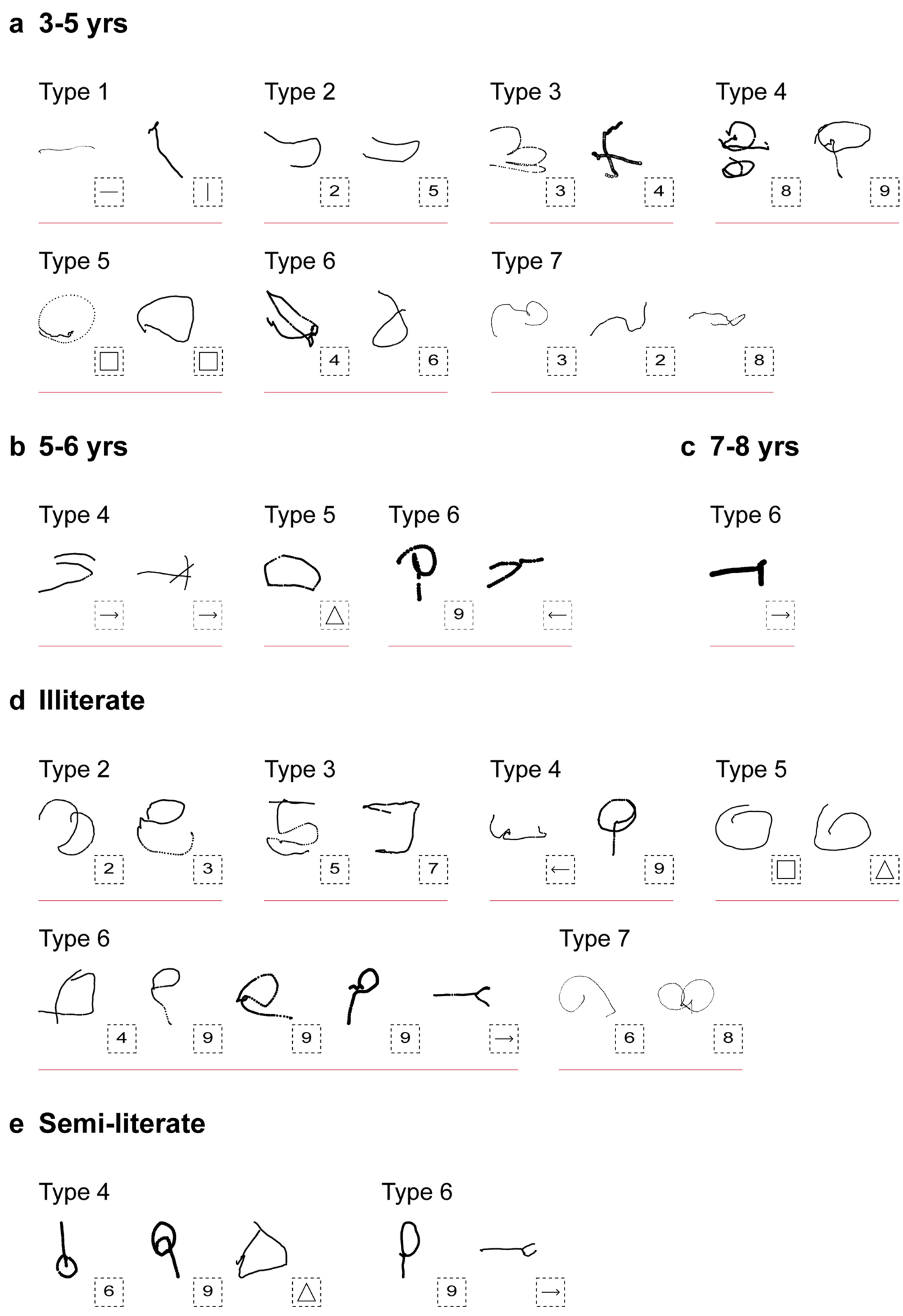

Fig. 4 Errors in the writing of the three groups of children and the two groups of adults. The symbol in the dashed box shows the reference stimulus while the bigger one on top of the box show the writing of participants. Literate adults performed well in all aspects of writing

Error types of illiterate, semi-illiterate, and literate adults

The types of errors made by illiterate individuals in writing are similar to that of children at 3–5 years old (Table 2). All the errors that were made by 3–5 years old children can be seen from their results. However, they seemed to have fewer type 1 errors (1 of 10 illiterate individuals failed to write horizontal or vertical lines straightly, all of them were able to write circles correctly, but 3, 4, and 6 out of the 21 participants in the 3–5 years old children group mis-wrote horizontal, vertical and circles, respectively). This observation is consistent with the fact that as adults, they had better abilities in fine motor control (Fig. 4d).

Semi-illiterate individuals only showed type 4 error (i.e., the relative position of the parts is wrong) and type 6 error

Table 2 The error rate of each type of error for each group of participants

			Error rates				
			3–5 years	5–6 years	6–7 years	Illiterate adults	Semi-literate adults
Type 1	Unable to draw straight horizontal or vertical lines	—; |	19.05%	\	\	\	\
Type 2	Unable to copy down the provided symbol's structure	2; 3; 5	47.62%	\	\	40.00%	\
Type 3	Neglecting (missing) important component or adding additional components	3; 4; 5; 7	57.14%	\	\	40.00%	\
Type 4	The relative position of the parts is wrong	8; 9; △; →; ←	57.14%	29.62%	\	30.00%	37.50%
Type 5	Mixing up triangles and squares, as they would often mistakenly draw a circle instead of a triangle or vice versa	□; △	71.43%	7.41%	\	60.00%	\
Type 6	Complete or partial mirror writing	4; 9; →; ←	28.57%	18.52%	3.57%	30.00%	12.50%
Type 7	Wrong global orientation	2; 3; 6; 8	28.57%	\	\	30.00%	\

(mirror writing) (Fig. 4e). Their error types are similar to those of 5–6 years old but with more mirror writing.

Literate adults performed well in all aspects of writing.

Discussion

This study investigated whether or not the learning of visuomotor transformation is specific to handwriting or it can be generalized from learning other visuomotor skills in everyday life and work. To address this question, we directly compared the performance between illiterate adults and young children (3–5 years old). Both groups have received no formal education. Compared to young children, illiterate adults have well-grown muscles and joints, and their visuomotor abilities is well-developed through daily work and chores. Yet, we found that illiterate adults performed similarly in handwriting to 3–5 years old children who have just started kindergarten. In other words, the visuomotor skills that these adults have acquired previously failed to generalize into their handwriting skills. This finding is surprising considering that the stimuli we used were all simple symbols and participants were given visual feedback and were allowed to correct their writing. It suggests that the learning of visuomotor skills have strong specificity.

Due to the difficulty in finding illiterate participants, we failed to perfectly match the age of illiterate, semi-illiterate and literate adult groups. This will not affect our conclusion, however, because our focus was on the comparison between illiterate and children participants. One may argue that age plays an important role in our illiterate participants' performance, as the mean age is 79.8 years old. However, although this groups of adults are the oldest group among adults, they demonstrated a clear understanding of our instructions, and were able to communicate clearly. Moreover, they were able to perform chores at home independently. Lastly, their performance in writing horizontal and vertical lines and circles suggests that they did in fact have well-functioning fine motor control. Thus, such argument would be highly unlikely. Importantly, the effect sizes for the Chi-square tests were between medium and large, therefore suggesting the reliability of our findings.

Interestingly, although our semi-illiterate participants received little to no formal education, they have shown less errors in their writing performance. These participants could recognize 1–60 Chinese characters, which suggests that they have previous experience in learning the structure and shape of different characters, mostly through observation in daily life. This suggests that daily practices of observing and recognizing characters improves writing ability and that social observation and cultural environment played a role in the symbolic development. This is consistent with Vygotsky's sociocultural theory emphasizes the role of social interactions and cultural environments in a child's learning and development (Vygotsky, 2012; Vygotsky & Cole, 1978). Overall, these findings are consistent with the previous finding of the close link between literacy and handwriting (Bramao et al., 2007; Ray et al., 2022).

Among all the errors, one unique type is mirror writing. It refers to writing in the opposite direction to normal, with the whole symbol or part of the symbol reversed. In our study, the most common symbol that showed mirror error are 4, 6, 7, 9, and arrows (partial mirror error). Consistent with the previous finding that modest reading practice, late in life, is suffice to break mirror invariance (i.e., recognizing a mirror image as the same object) (Pegado et al., 2014), we found that 5 out of 21 participants in the 3–5 years old group, 4 out of 27 participants in the 5–6 years old group and 0 out of 28 participants in the 6–7 years old group made mirror errors. For adults, illiterate participants showed the most mirror errors (4 out of the 10 participants). The semi-illiterate participants made fewer mirror errors (2 out of 8), while the literate participants made no mirror errors.

Another interesting observation is that the 3–5 years old children and illiterate adults often mixed up triangles, squares and circles. They would often write down one when in fact the stimulus shown the other one. This is not a result of their inability to write sharp edges and angles, as they could write down numbers such as 4 and 7 without mistakes. Instead, we think this reflects that the global topological property is a basic factor in visual perception and visuomotor transformation (Chen, 1982). From the perspective of topology, a solid triangle, a solid square, and a solid circle are equivalent because a square or triangle can be deformed into a circle without breaking it.

Previous studies show that literacy improves the early visual processing (Dehaene et al., 2015). Then is it possible that children or adults made errors just because they could not process the information visually, not because they could not transform visual information into precise action commands and then produce appropriate motor actions? This is less likely because all the participants had normal or corrected-to-normal vision and reported that they could see our stimuli clearly. Although we did not test their performance in visual recognition, children at 2.5- 3 years old should be able to identify the majority of basic shapes according to previous studies (Verdine et al., 2016). The illiterate participants might not be able to name the numbers or arrows, but the fact that they can recognize roads and other everyday objects and faces suggests that they have the ability of visual recognition and were able to process visual information.

In addition, it should also be noted that the stimulus was always presented on the screen and participants were allowed to see their own writing and correct their writing if they wanted. Therefore, the errors made by illiterate participants could not be attributed to their limit in working memory and attention, or their unfamiliarity with the stimulus.

Our findings also bear important implications for symbolic development and learning in the early childhood. Symbolic development can be explained as the developmental levels of understanding visual information. Piaget's theory of cognitive development proposes that children acquire eye-hand coordination in early stages (sensorimotor and preoperational) and subsequently develop the ability to use symbols in speech and writing (Barrouillet, 2015; Huitt & Hummel, 2003; Piaget, 2003; So, 1964). In our study, participants were asked to copy the symbols, which requires both sensorimotor skills and symbolic processing. The finding that children but not illiterate adults' performance got better suggests that the symbolic recognition taught in school plays a critical role in sensorimotor development. In other words, in contrast to Piaget's theory that children first develop sensorimotor skills and then symbolic processes, we suggest that sensorimotor and symbolic skills may develop simultaneously and facilitates each other.

Importantly, our findings also provoke deep thoughts on the phenomenon that more and more children rely on typing on the keyboard instead of handwriting. There has already been research on how keyboard typing influences cognitive development as compared to handwriting (Connelly et al., 2007; Kiefer et al., 2015; Longcamp et al., 2005; Suggate et al., 2023). One clear difference between typing and handwriting is that during keyboard typing, users simply click on the key of symbols without needing to process the visual shape and structure of symbols. Our findings that handwriting requires specific visuomotor training and sensorimotor and symbolic learning facilitate each other suggest that the early and frequent use of typing may affect children's handwriting and, as a result, symbolic learning (Li & James, 2016).

One limitation of our study is the absence of cognitive performance testing for the children participants, as reading assessments were only given to the adult participants. Additionally, we did not assess potential dyslexia and dyscalculia in the children. Future research may further the investigation on the relationship between handwriting and other cognitive measures, and examine the correlation between individual differences in sensorimotor abilities (Wang et al., 2022) (such as handwriting), cognitive measures and performance in school.

In conclusion, our study suggests that visuomotor learning for handwriting has strong specificity and therefore requires specific training. The observation that semi-illiterate participants could write well suggests that intentional observation of stimulus outside of school also helps writing. Overall, our findings provide new insights into the learning of visuomotor skills required for handwriting and highlight the importance of specific training for handwriting intervention.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12144-023-05009-x.

Author contributions C. Z and J.C designed the study. C.Z performed the research. C.Z., C.W., J, G., Z.D., and J.C analyzed the data. C.W., Z.D. and J.C. wrote the manuscript. All authors have read and approved the final version of the manuscript.

Funding This research was supported by the National Natural Science Foundation of China (No. 31970981), the National Science and Technology Innovation 2030 Major Program (STI2030-Major Projects 2022ZD0204802).

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval The study was approved by the Human Research Ethics Board at South China Normal University (SCNU) and the methods were in accordance with the guidelines established in the Declaration of Helsinki.

Informed Consent Written informed consent was obtained from the adult participants or their family members. For child participants, informed consent was taken from their parents. All participants received monetary compensation for their time. Informed consent was obtained from the girl's parents for publication of the girl's image in Fig. 1A in a journal article.

Conflicts of Interest The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Ahissar, M., & Hochstein, S. (1997). Task difficulty and the specificity of perceptual learning. *Nature, 387*(6631), 401–406.

Amundson, S. (1992). Handwriting: Evaluation and intervention in school setting. *Development of hand skills in the child*.

Barrouillet, P. (2015). Theories of cognitive development: From Piaget to today. *Developmental Review, 38*, 1–12.

Beery, K., & Buktenica, N. (1989). *Developmental test of visual-motor integration-Revised*. Follett.

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.

Brainard, D. H., & Vision, S. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.

Bramao, I., MendonCA, A., Faísca, L., Ingvar, M., Petersson, K. M., & Reis, A. (2007). The impact of reading and writing skills on a visuo-motor integration task: A comparison between illiterate and literate subjects. *Journal of the International Neuropsychological Society, 13*(2), 359–364.

Cai, Q., & Brysbaert, M. (2010). SUBTLEX-CH: Chinese word and character frequencies based on film subtitles. *Plos One, 5*(6), e10729.

Chang, S.-H., & Yu, N.-Y. (2005). Evaluation and classification of types of Chinese handwriting deficits in elementary schoolchildren. *Perceptual and Motor Skills, 101*(2), 631–647.

Chen, L. (1982). Topological structure in visual perception. *Science, 218*(4573), 699–700.

Connelly, V., Gee, D., & Walsh, E. (2007). A comparison of keyboarded and handwritten compositions and the relationship with transcription speed. *British Journal of Educational Psychology, 77*(Pt 2), 479–492. https://doi.org/10.1348/000709906x116768

Cornhill, H., & Case-Smith, J. (1996). Factors that relate to good and poor handwriting. *The American Journal of Occupational Therapy, 50*(9), 732–739.

Crist, R. E., Kapadia, M. K., Westheimer, G., & Gilbert, C. D. (1997). Perceptual learning of spatial localization: Specificity for orientation, position, and context. *Journal of Neurophysiology, 78*(6), 2889–2894.

Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: Behavioural and cerebral changes induced by reading acquisition. *Nature Reviews Neuroscience, 16*(4), 234–244.

Fahle, M. (2005). Perceptual learning: Specificity versus generalization. *Current Opinion in Neurobiology, 15*(2), 154–160.

Fancher, L. A., Priestley-Hopkins, D. A., & Jeffries, L. M. (2018). Handwriting Acquisition and Intervention: A Systematic Review. *Journal of Occupational Therapy, Schools, & Early Intervention, 11*(4), 454–473. https://doi.org/10.1080/19411243.2018.1534634

Feder, K. P., & Majnemer, A. (2007). Handwriting development, competency, and intervention. *Developmental Medicine & Child Neurology, 49*(4), 312–317.

Huitt, W., & Hummel, J. (2003). Piaget's theory of cognitive development. *Educational psychology interactive*, *3*(2).

Irvine, D. R., Martin, R. L., Klimkeit, E., & Smith, R. (2000). Specificity of perceptual learning in a frequency discrimination task. *The Journal of the Acoustical Society of America, 108*(6), 2964–2968.

Karlsdottir, R., & Stefansson, T. (2002). Problems in developing functional handwriting. *Perceptual and Motor Skills, 94*(2), 623–662.

Kiefer, M., Schuler, S., Mayer, C., Trumpp, N. M., Hille, K., & Sachse, S. (2015). Handwriting or Typewriting? The Influence of Pen- or Keyboard-Based Writing Training on Reading and Writing Performance in Preschool Children. *Advances in Cognitive Psychology, 11*(4), 136–146. https://doi.org/10.5709/acp-0178-7

Lei, Y., & Wang, J. (2014). Prolonged training does not result in a greater extent of interlimb transfer following visuomotor adaptation. *Brain and Cognition, 91*, 95–99. https://doi.org/10.1016/j.bandc.2014.09.004

Li, J. X., & James, K. H. (2016). Handwriting generates variable visual output to facilitate symbol learning. *Journal of Experimental Psychology: General, 145*(3), 298–313. https://doi.org/10.1037/xge0000134

Longcamp, M., Zerbato-Poudou, M. T., & Velay, J. L. (2005). The influence of writing practice on letter recognition in preschool children: A comparison between handwriting and typing. *Acta Pathologica, Microbiologica, Et Immunologica Scandinavica, 119*(1), 67–79. https://doi.org/10.1016/j.actpsy.2004.10.019

Love, J., Selker, R., Marsman, M., Jamil, T., Dropmann, D., Verhagen, J., Ly, A., et al. (2019). JASP: Graphical statistical software for common statistical designs. *Journal of Statistical Software, 88*, 1–17.

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

Maldarelli, J. E., Kahrs, B. A., Hunt, S. C., & Lockman, J. J. (2015). Development of early handwriting: Visual-motor control during letter copying. *Developmental Psychology, 51*(7), 879–888. https://doi.org/10.1037/a0039424

Marr, D., Cermak, S., Cohn, E. S., & Henderson, A. (2003). Fine motor activities in Head Start and kindergarten classrooms. *The American Journal of Occupational Therapy, 57*(5), 550–557.

Nozaki, D., Kurtzer, I., & Scott, S. H. (2006). Limited transfer of learning between unimanual and bimanual skills within the same limb. *Nature Neuroscience, 9*(11), 1364–1366.

Pegado, F., Nakamura, K., Braga, L. W., Ventura, P., Nunes Filho, G., Pallier, C., Jobert, A., et al. (2014). Literacy breaks mirror invariance for visual stimuli: A behavioral study with adult illiterates. *Journal of Experimental Psychology: General, 143*(2), 887.

Pelli, D. G., & Vision, S. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442.

Piaget, J. (2003). Part I: Cognitive development in children--piaget development and learning. *Journal of Research in Science Teaching, 40*.

Ray, K., Dally, K., Rowlandson, L., Tam, K. I., & Lane, A. E. (2022). The relationship of handwriting ability and literacy in kindergarten: A systematic review. *Reading and Writing*, 1–37.

Sandler, A. D., Watson, T. E., Footo, M., Levine, M. D., Coleman, W. L., & Hooper, S. R. (1992). Neurodevelopmental study of writing disorders in middle childhood. *Journal of Developmental and Behavioral Pediatrics, 1*, 17–23.

So, I. (1964). Cognitive development in children: Piaget development and learning. *Journal, of Research in Science Teaching, 2*, 176–186.

Stark-Inbar, A., Raza, M., Taylor, J. A., & Ivry, R. B. (2017). Individual differences in implicit motor learning: Task specificity in sensorimotor adaptation and sequence learning. *Journal of Neurophysiology, 117*(1), 412–428.

Suggate, S. P., Karle, V. L., Kipfelsberger, T., & Stoeger, H. (2023). The effect of fine motor skills, handwriting, and typing on reading development. *J Exp Child Psychol, 232*, 105674. https://doi.org/10.1016/j.jecp.2023.105674

Tremblay, S., Houle, G., & Ostry, D. J. (2008). Specificity of speech motor learning. *Journal of Neuroscience, 28*(10), 2426–2434.

Tseng, M. H., & Hsueh, I. P. (1997). Performance of school-aged children on a Chinese handwriting speed test. *Occupational Therapy International, 4*(4), 294–303.

Van Waelvelde, H., Hellinckx, T., Peersman, W., & Smits-Engelsman, B. C. (2012). SOS: A screening instrument to identify children with handwriting impairments. *Physical & Occupational Therapy in Pediatrics, 32*(3), 306–319. https://doi.org/10.3109/01942638.2012.678971

Verdine, B. N., Lucca, K. R., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2016). The Shape of Things: The Origin of Young Children's Knowledge of the Names and Properties of Geometric Forms. *Journal of Cognition and Development, 17*(1), 142–161. https://doi.org/10.1080/15248372.2015.1016610

Vygotsky, L. S., & Cole, M. (1978). *Mind in society: Development of higher psychological processes*. Harvard university press.

Vygotsky, L. S. (2012). *Thought and language*. MIT press.

Wang, C., Gao, J., Deng, Z., Zhang, Y., Zheng, C., Liu, Xiaoli, Sperandio, I., & Chen, J. (2022). Extracurricular sports activities modify the proprioceptive map in children aged 5–8 years. *Scientific Reports, 12*(1), 9338. https://doi.org/10.1038/s41598-022-13565-8

Wang, R., Zhang, J.-Y., Klein, S. A., Levi, D. M., & Yu, C. (2012). Task relevancy and demand modulate double-training enabled transfer of perceptual learning. *Vision Research, 61*, 33–38. https://doi.org/10.1016/j.visres.2011.07.019

Wiley, R. W., Wilson, C., & Rapp, B. (2016). The effects of alphabet and expertise on letter perception. *Journal of Experimental Psychology: Human Perception and Performance, 42*(8), 1186.

Xiao, L.-Q., Zhang, J.-Y., Wang, R., Klein, S. A., Levi, D. M., & Yu, C. (2008). Complete transfer of perceptual learning across retinal locations enabled by double training. *Current Biology, 18*(24), 1922–1926.

Xiong, Y.-Z., Zhang, J.-Y., & Yu, C. (2016). Bottom-up and top-down influences at untrained conditions determine perceptual learning specificity and transfer. *eLife, 5*, e14614.

Yin, C., Bi, Y., Yu, C., & Wei, K. (2016). Eliminating direction specificity in visuomotor learning. *Journal of Neuroscience, 36*(13), 3839–3847.

Yokoi, A., Bai, W., & Diedrichsen, J. (2017). Restricted transfer of learning between unimanual and bimanual finger sequences. *Journal of Neurophysiology, 117*(3), 1043–1051.

Zhang, J.-Y., Zhang, G.-L., Xiao, L.-Q., Klein, S. A., Levi, D. M., & Yu, C. (2010). Rule-based learning explains visual perceptual learning and its specificity and transfer. *Journal of Neuroscience, 30*(37), 12323–12328.