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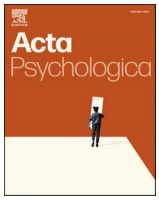

The role of handwriting in English word acquisition among elementary students

Yang Ying, Zhang Huixin, Wu Yunxia, Li Wenhui [*,1]

College of Preschool and Primary Education, Shenyang Normal University, Shenyang, China

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ABSTRACT

In order to investigate whether handwriting has an advantage in learning word form, sound, and meaning, this study randomly selected 40 elementary school student participants (20 males, 20 females, aged 11.4 ± 1.34 years). Using an experimental approach, we compared the learning outcomes of word sound matching, word meaning matching, and word form judgment tasks under two conditions: handwriting and visual learning. After three consecutive days of learning and testing, we found that handwriting generally outperformed visual learning in terms of accuracy and response time in word form, sound, and meaning learning. Additionally, we observed differences in the timing of significant discrepancies in learning outcomes between the two methods across the three tasks. Specifically, in terms of accuracy, discrepancies first appeared in the word sound matching task on the first day, followed by the word form judgment task, and lastly the word meaning matching task. Regarding response time, significant differences between learning methods first emerged in the word form judgment task, followed by the word sound and word meaning tasks. Thus, combining accuracy and response time data, we conclude that handwriting is more advantageous than visual learning for word acquisition, with a differential impact on word form, sound, and meaning, where word form and sound are prioritized over meaning.

1. Introduction

With the advancement of technology and the internet, computers have become essential tools in our daily work and studies (Guilbert et al., 2019). From the perspective of work efficiency, using electronic devices for text input and output may be faster, but handwriting possesses irreplaceable advantages. The motor advantage hypothesis explains this phenomenon, with its core premise being that, in comparison to other methods of inputting information, handwriting yields better learning outcomes (Kiefer et al., 2015; Longcamp et al., 2005). Furthermore, this hypothesis has been supported by numerous empirical studies (Ihara et al., 2021; Mayer et al., 2020; Van der Meer & Van der Weel, 2017). Although the hypothesis has garnered substantial support, the mechanisms driving the advantages of handwriting require further exploration. In the following sections, we will discuss both the reasons for the existence of the handwriting advantage and the controversies surrounding it.

1.1. Reasons for the existence of handwriting advantage

1.1.1. Handwriting increases attention to words more than visual learning

One of the focal points for researchers is the difference in attentional engagement between handwriting and other learning modalities such as visual learning (Zemlock et al., 2018). In the study by Zemlock et al. (2018), a comparison was made between handwriting and visual learning. Although there was no explicit measurement of attentional differences between the two learning methods, they suggested that the motor system involved in handwriting is more effective in capturing attention than pure visual tasks. Therefore, handwriting is a learning modality that requires a significant amount of attention, especially when learning a new word or sequence of actions (Swett et al., 2010). In the research conducted by Seyll et al. (2022), to compare the differences in attentional engagement during learning new graphical shapes among handwriting, typing, and composition, a dual-task detection paradigm was employed. The reaction time of the secondary task, an audio-visual detection task, served as the primary indicator of attentional engagement. The underlying principle is based on the assumption that the total

* Corresponding author at: College of Preschool and Primary Education, Shenyang Normal University, 253 North Huanghe Street, Shenyang City, Liaoning Province 110034, China.
E-mail address: llwwhh1984@126.com (L. Wenhui).
[1] Present/permanent address: 253 Huanghe North Street, Shenyang City, Liaoning Province, China.

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attentional resources are fixed (Woollacott & Shumway-Cook, 2002). When there is an excessive allocation of attention to the primary task, attentional resources for the secondary task diminish, leading to longer reaction times (Zanone et al., 2011). The results indicated that handwriting had longer reaction times compared to the other two methods, suggesting that handwriting requires more attentional engagement (Seyll et al., 2022). This is because during handwriting, more focus is directed towards the graphical aspects, thereby aiding the handwriting process. This finding also helps explain Seyll et al.'s (2020) earlier research, which suggested that the advantage of handwriting in synthetic training results from increased attentional engagement.

1.1.2. Handwriting as a result of multisensory processing

Handwriting is a method that involves the presentation of symbols, letters, and words in textual form, utilizing tools such as pens, pencils, paper, or boards (Mangen et al., 2015). This process requires the simultaneous involvement of multiple senses such as vision, touch, and proprioception (Fogassi & Gallese, 2004), whereas visual learning predominantly engages the visual sense (Guan & Zhao, 2019). It is the engagement of multiple senses in handwriting that facilitates the coupling between action and perception, thereby enhancing sensorimotor skills and promoting word learning (Kiefer et al., 2015). Research utilizing brain imaging techniques has clearly demonstrated how handwriting activates brain regions associated with sensorimotor skills (Chen et al., 2002). The impact of handwriting on sensorimotor skills arises from the requirement to conform to the shape of letters, leading to a correspondence between the movements during handwriting and the target letters (Araújo et al., 2022). By integrating visual, motor, and proprioceptive senses, and forming a continuity in both time and space, handwriting facilitates learning of materials, especially with regard to letters associated with specific handwriting actions (Mangen et al., 2015).

1.1.3. Handwriting allows more time for learning English words than visual learning

When engaging in handwriting, the coordination between visual and hand movements is necessary to master this skill (Stevenson & Just, 2014). Handwriting English words involves first perceiving the shapes and sizes of the letters through visual gaze (Longcamp et al., 2005), followed by the execution of hand movements (Pepe et al., 2012). In a study by Sita and Taylor (2015) comparing adults' handwriting and visual learning of the same word, it was found that handwriting resulted in more frequent and longer visual fixations. Moreover, the fixation locations differed between the two methods, with visual learning focusing more around the center of the word, whereas handwriting involved fixating on each letter in sequence from left to right. In other words, although both handwriting and visual learning involve visual fixations, their specific durations and frequencies differ. In addition to fixations on the word, there is also additional attention paid to the word. This is because when handwriting a word, some time is initially spent perceiving the shapes of the letters through visual fixations before beginning the process of handwriting the letters. However, as familiarity with the material increases, the fixation time decreases. As participants become more familiar with the shapes of each letter through repeated viewing, handwriting becomes easier, allowing more time to be devoted to the actual act of handwriting (Fears & Lockman, 2018).

1.1.4. Handwriting involves more detailed visual processing than visual learning

Recently, a new explanation for the handwriting advantage has been proposed, primarily by Seyll et al. (2020). They argue that one key reason for the handwriting advantage lies in the more detailed visual processing involved in handwriting. Wong et al.'s (2018) research supported this notion. In their study, even proficient readers, after multiple exposures to experimental materials, could not recall alternative forms of the letter "g," possibly due to a lack of related handwriting experience. This suggests that even after extensive visual exposure, sufficiently detailed representations cannot be formed (Seyll & Content, 2022).

To verify whether handwriting indeed involves more detailed visual processing, Seyll et al. (2020) conducted a study with adults, introducing a new learning method called composition learning alongside handwriting and typing. Composition learning requires detailed visual analysis of the learning content but does not involve related handwriting movements. During composition learning, participants were presented with a set of basic visual features related to constructing symbols. They then had to select the appropriate visual features and drag them to the corresponding positions to form the target symbol. Subsequently, participants underwent a four-alternative forced-choice recognition test (4AFC) and a novelty recognition test, in which a learned symbol and three distractors were presented in the 4AFC task, and 12 learned symbols and their mirrors were presented in the novelty recognition test (as in Longcamp et al., 2006). The results showed that handwriting and composition learning had similar outcomes, both outperforming typing in symbol recognition. Therefore, one crucial reason for the handwriting advantage is the result of detailed visual analysis. To verify whether this result applies to preschool children, Seyll et al. (2022) conducted a similar 4AFC task, finding consistent results with those of adults, further confirming that detailed visual analysis is one of the reasons for the handwriting advantage.

1.2. Controversy surrounding the handwriting advantage

While most studies have demonstrated the advantages of handwriting in character and letter recognition and learning, different results have emerged in studies related to spelling and recognition of English words. Some research, focusing on elementary school students, examined the learning effects of word spelling and recognition under typing and handwriting conditions using newly created non-words as learning materials. The results showed similar effects after practice in both conditions, indicating no additional advantage of handwriting (Ouellette & Tims, 2014). Several reasons account for this: Firstly, concerning the structure of words, when learning letters through handwriting, the motor trajectories of handwriting establish a correspondence with the letters (Longcamp et al., 2005). However, for word learning, words are composed of multiple letters arranged in a certain sequence. Once the correct sequence of letters is mastered, word learning transforms into learning the connections between word letters and their pronunciation, which only requires visual presentation and pronunciation. The handwriting process involves arranging letters according to their pronunciation, which is not sensitive to the motor actions involved in handwriting (Chen et al., 2016).

Secondly, it relates to the characteristics of words. Some researchers have analyzed this based on the characteristics of the English language, suggesting that English has strong "grapheme-phoneme" correspondence rules, meaning that the pronunciation can be inferred from the spelling (Zhang & Yang, 2004), meaning that pronunciation influences word spelling. Participants, having already mastered the shapes and pronunciation of each letter in a word, may promote the learning of word forms according to orthographic-phonological correspondence rules, regardless of whether they use handwriting or typing, thereby diminishing the effects of practice (Chen et al., 2016). Although some studies have found advantages by presenting word shapes without phonemic information, this doesn't reflect real English learning situations. In actual English word learning, learners usually acquire the pronunciation first and then derive the spelling from the sound. Therefore, in English word learning, interference from "grapheme-phoneme" correspondence rules cannot be eliminated. This interference may weaken the advantage of handwriting.

Thirdly, it is related to the cognitive abilities of participants. Researchers have attributed the lack of handwriting advantage to the idea that handwriting consumes more cognitive resources, making it age-

dependent. If individuals have limited cognitive capacity, they may not be able to invest additional resources when learning characters or words through handwriting, and the advantages of handwriting may not manifest (Tan et al., 2013; Van Merrienboer & Sweller, 2005). In addition to questioning the existence of the handwriting advantage in word learning, some research suggests that the advantages of handwriting and typing in learning require further investigation (Morehead et al., 2019). In summary, the existence of the handwriting advantage in letter and word learning is controversial. Therefore, exploring the advantages of handwriting in word learning is one of the objectives of this study.

1.3. The importance of effective word learning methods

Words serve as the foundation for English reading and writing, playing a crucial role in the development of written language (Jackson et al., 2019). The ultimate goal of word learning is to establish representations encompassing word pronunciation, vocabulary, and meaning (Hoover et al., 2010). Specifically, pronunciation refers to the sound of words; vocabulary refers to the letter combinations of words, i.e., word forms; and meaning refers to the significance of words (Storkel, 2009). Thus, enhancing learning of word forms, pronunciation, and meanings is beneficial for mastering words.

Words are the basic units of language learning, Acquiring an adequate vocabulary is one aspect of word learning (Zhang et al., 2020), with differences in vocabulary existing as early as kindergarten, becoming more pronounced by elementary school (Von Hippel et al., 2018). In China, formal English learning typically begins in the third grade of elementary school (Li et al., 2007). Initially, the focus is on learning letters, pronunciation, and basic daily vocabulary. Word learning is not yet the main focus during this stage, primarily aimed at cultivating students' interest in English. As students grow older, by the sixth grade, the focus shifts to developing students' listening, speaking, reading, and writing skills in words and sentences (Wu, 2011). Additionally, the sixth grade marks the period of transitioning from elementary to junior high school, with English being a crucial subject in entrance examinations. However, due to the widening gap in vocabulary, the polarization in word learning becomes more apparent (Sun & Meng, 2021). Therefore, investigating effective word learning methods at this stage becomes necessary. Research has shown that students' writing speed is closely related to classroom note-taking, which, in turn, has a direct correlation with students' academic performance. Thus, handwriting is a vital learning method for elementary school students (Peverly et al., 2014).

1.4. The necessity of this study

In recent years, there have been numerous studies assessing the learning effects of word form, word sound, and meaning. These include tasks such as auditory lexical decision and rapid naming tasks to assess word form learning (Hein & Kauschke, 2020), contextual learning of words by embedding them into sentences or stories and testing participants through reading or defining tasks (Norman et al., 2023; van den Broek et al., 2022), and using picture-word matching tasks to test the learning effects of pictures on word meanings (Boddaert et al., 2021). Although there are various tasks to assess mastery of word forms, pronunciations, and meanings, there are few studies investigating the specific sequential effects of handwriting on word form, pronunciation, and meaning. Most existing studies have focused on the controversy surrounding the handwriting advantage in word learning. Therefore, in this study, in order to explore the advantages and specific sequence effects of handwriting on word acquisition, we mainly designed three tasks: word form judgment task, word sound matching task and word meaning matching task.

Previous research has primarily focused on the advantages of handwriting in the context of one's native language (Morehead et al., 2019; Mueller & Oppenheimer, 2014; Otsuka & Murai, 2023). There has been relatively limited research from the perspective of second language learning (Guan et al., 2011, 2021; Mayer et al., 2020). Furthermore, results regarding handwriting advantages in letter and character recognition do not necessarily translate to handwriting advantages in word learning. While handwriting advantages exist in letter and character recognition, the existence of handwriting advantages in word spelling and recognition remains controversial. Additionally, most studies have compared handwriting with typing (Ihara et al., 2021; Mangen et al., 2015; Suggate et al., 2023), with fewer studies comparing handwriting with visual learning (Guan et al., 2021; Wiley & Rapp, 2021; Zemlock et al., 2018). Based on this, we propose hypothesis 1: Handwriting is more advantageous than visual learning (reading only) for word form, word sound, and meaning learning. Given that most studies on handwriting and word learning have focused on the existence of handwriting advantages and have rarely investigated the sequential effects on word form, word sound, and meaning, we propose hypothesis 2: The sequential effects of handwriting on word form, word sound, and meaning are different, with word form being influenced first, followed by word sound, and finally meaning.

2. Experimental method

2.1. Participants

In October 2018, 40 students were randomly selected from two sixth-grade classes in a primary school in Shenyang. Each class consisted of 10 boys and 10 girls. The average age of the males was 11.45 ± 0.510 years, and the average age of the females was 11.30 ± 0.470 years. To examine whether there were significant differences in English scores among the 40 participants, an independent samples *t*-test was conducted between the two classes, and the results are presented in Table 1. All participants met the following criteria: (1) had not received extracurricular English tutoring, (2) had normal vision, (3) had no mental disorders, and (4) were right-handed. Note: The choice of right-handed participants was made for two reasons: first, to ensure uniformity among participants and minimize the potential influence of left-handedness on handwriting, and second, right-handedness is more common and facilitates participant selection. This study was approved by the Ethics Committee of the College of Preschool and Elementary Education at Shenyang Normal University (Approval No.: CPPE201805160002). Informed consent was obtained from all participants and their parents.

2.2. Experimental design

The experiment employed a 2 (Learning Method: Handwriting Learning; Visual Learning) × 2 (Match: Matching; Non-matching) mixed factorial design for word-sound and word-meaning tasks. Learning method served as a between-subjects variable, while matching condition was a within-subjects variable. A two-way repeated measures analysis of variance (ANOVA) was used to analyze the data. The word-form judgment task used a between-subjects design, and data analysis was conducted using independent samples *t*-tests. The dependent variables in the experiment were reaction times and accuracy for the two groups of participants. The Learning Method variable included Handwriting Learning, where participants learned words through writing, and Visual Learning, where participants learned words visually without any tools, simply by reading. The Match variable consisted of Matching, which referred to word-sound or word-meaning matching tasks. In word sound matching tasks, participants had to judge if the heard pronunciation of a

Table 1
Independent samples t-test for English scores.

Class	Score	*t*	*df*	*p*
Class1	86.53 ± 12.71	−0.26	58	0.79
Class2	86.72 ± 13.46			

word matched the given pronunciation. In word-meaning matching tasks, participants had to judge if the meaning of the word matched the presented meaning on the screen. By comparing the accuracy and reaction times of the three tasks under both handwriting learning and visual learning, Hypothesis 1 was tested. The higher the accuracy and the lower the reaction times, the better the performance.

2.3. Experimental materials

The selection process for experimental materials is as follows (Table 2):

In this experiment, the learning group words refer to the words that the participants needed to learn. In the novel word group, new words are the ones that appeared as new words in the tasks of word-form judgment, word-sound matching, and word-meaning matching. Pseudowords in the novel word group refer to words that were created based on the 20 recognized English words, following orthographic rules, to make their word forms similar.

Independent samples t-tests were conducted to compare the number of letters and the stroke count of meanings between the learning group words and the new-different group words. The results showed no significant differences, $t_{\text{letter count}} = -1.505$, $df_{\text{letter count}} = 164$, $p_{\text{letter count}} = 0.311$, $t_{\text{stroke count}} = 0.201$, $df_{\text{stroke count}} = 164$, $p_{\text{stroke count}} = 0.752$. The words learned were assessed in both visual and handwritten learning contexts.

2.4. Experimental procedure

The experimental procedure was divided into two phases: the learning training phase and the learning testing phase. *E*-prime software was used for programming.

Learning Training: The learning training spanned three days and was programmed using E-prime software. Participants were situated in a closed, unmanned computer lab with adjusted seating and screens. To familiarize the participants with the experimental steps as quickly as possible, the experimental personnel explained the procedure and requirements before the start of the experiment. Participants were divided into two groups. The screen initially displayed two English words for adaptation, followed by 20 English words for formal learning.

Learning Testing: The learning testing was conducted after each day's word learning training and comprised three parts: word form judgment, word sound matching, and word meaning matching. In the word form judgment task, participants were presented with 10 words from the learning group and 10 words from the new group (5 new words and 5 pseudo words), and they were asked to determine whether each word belonged to the learning group. Similarly, in the word sound matching and word meaning matching tasks, there were 10 matching words (sound/meaning) and 10 mismatching words (sound/meaning). The specific experimental procedures are as follows (Table 3):

Table 2
The selection process for experimental materials.

Step1	Based on the 3rd-grade English textbook (Oxford edition), 120 English words were selected for the pre-test. The pre-test involved 10 students from a different class, who were not part of the experimental group. The English scores of these 10 students were compared to the English scores of the experimental group using an independent samples t-test, and the result was $p > 0.05$.
Step2	A panel of 10 students was selected to evaluate the 120 English words. Out of these, 20 words were recognized in terms of pronunciation, form, and meaning, 40 words were completely unrecognized, and the remaining 60 words had uncertain recognition. Therefore, all 60 words with uncertain recognition were excluded.
Step3	The 20 recognized words were modified for subsequent sound-form-meaning tests. The 40 completely unrecognized words were divided into two equal groups. One group was used for word learning during the experiment, and the other group served as new words. This resulted in two sets of words: the learning group words and the novel word group (consisting of both new and pseudo-words).

2.5. Statistical analysis

Data from both groups of participants were entered into the *E*-prime software. Independent samples t-tests were conducted using SPSS 19.0 software for the word form judgment task, while repeated measures analysis of variance (ANOVA) was employed for the word sound matching and meaning matching tasks. With $p < 0.05$ indicating statistical significance.

3. Experimental results

3.1. Word-sound matching task

The results of task accuracy indicate a significant main effect of learning modality on the first day of the experiment, with handwriting learning showing higher accuracy than visual learning ($F_1(1, 38) = 5.71$, $p_1 = 0.02$, $\eta_p^2 = 0.13$). There was also a significant main effect of matching condition, with higher accuracy in the matching condition than the non-matching condition ($F_1(1, 38) = 6.67$, $p_1 = 0.01$, $\eta_p^2 = 0.15$). However, there was no significant interaction between learning mode and matching condition. On the second day, there was a significant main effect of learning mode, with handwriting learning showing higher accuracy than visual learning ($F_2(1, 38) = 4.68$, $p_2 = 0.04$, $\eta_p^2 = 0.11$). The main effect of matching condition was not significant, and there was no significant interaction between learning mode and matching condition. On the third day, there was a significant main effect of learning mode, with handwriting learning showing higher accuracy than visual learning ($F_3(1, 38) = 5.63$, $p_3 = 0.02$, $\eta_p^2 = 0.13$). There was also a significant main effect of matching condition, with higher accuracy in the matching condition compared to the non-matching condition

Table 3
Experimental procedures.

Step1	Learning training	Adaptive learning	The form, sound and meaning of two English words appeared on the screen to allow subjects to adapt
		Formal learning	The gaze symbol "+" appears 2000 ms The word form that needs to be learned appears 5000 ms The pronunciation of the word appears 5000 ms The meaning of the word appears 5000 ms There was a pause of 15 s, during which the word form appeared again on the screen. The handwriting group learned the words through pen and paper, and the visual group learned the words by watching the screen. End after hearing the beep
Step2	learning testing	word form judgment	The gaze symbol "+" appears 2000 ms A word form appears for 5000 ms The screen is blank for 3000 ms. At this time, press the J key for words that belong to the learning group, and press the F key for words that do not belong to the learning group.
		word sound matching	The gaze symbol "+" appears 2000 ms The word form that needs to be learned appears 5000 ms The pronunciation of the word appears 5000 ms The screen is blank for 3000 ms. At this time, press the J key for words that belong to the learning group, and press the F key for words that do not belong to the learning group.
		Word meaning matching	The procedure was the same as for the word-sound matching task.

($F_3(1, 38) = 21.30$, $p_3 < 0.05$, $\eta_p^2 = 0.36$). However, there was no significant interaction between learning mode and matching condition.

The results of task reaction time indicate that the main effects of learning modality and matching condition were not significant across the three consecutive days of the experiment. Additionally, there was no significant interaction between learning modality and matching condition over the three consecutive days (Table 4).

3.2. Word meaning matching task

From the perspective of accuracy, on the first day of the experiment, there were no significant main effects for learning mode ($F_1(1, 38) = 0.21$, $p_1 = 0.65$, $\eta_p^2 = 0.01$) or matching condition ($F_1(1, 38) = 0.49$, $p_1 = 0.49$, $\eta_p^2 = 0.01$). The interaction between learning mode and matching condition was also not significant. On the second day, there was a significant main effect for learning mode ($F_2(1, 38) = 9.51$, $p_2 = 0.01$, $\eta_p^2 = 0.20$), with handwriting learning achieving higher accuracy than visual learning. There was also a significant main effect for matching condition ($F_2(1, 38) = 10.09$, $p_2 = 0.003$, $\eta_p^2 = 0.21$), with higher accuracy in the matching condition compared to the non-matching condition. Furthermore, there was a significant interaction between learning mode and matching condition ($F(1, 38) = 5.41$, $p = 0.03$, $\eta_p^2 = 0.13$). Post-hoc analyses revealed that under matching conditions, there was a significant difference in learning mode ($F(1, 38) = 15.04$, $p = 0.02$, $\eta_p^2 = 0.28$), with handwriting learning achieving higher accuracy. However, under non-matching conditions, the learning mode did not reach statistical significance. This indicates that on the second day, handwriting learning did not show a substantial advantage over visual learning. On the third day, there was a significant main effect for learning mode ($F_3(1, 38) = 13.45$, $p_3 = 0.03$, $\eta_p^2 = 0.26$), with handwriting learning achieving higher accuracy than visual learning. There was no significant main effect for matching condition, and the interaction between learning mode and matching condition was not significant.

The results of reaction time indicate that the main effects of learning modality and match type were not significant across the three consecutive days of the experiment. Additionally, there was no significant interaction between learning modality and match type over the three days (Table 5).

3.3. Vocabulary judgment task

From the perspective of accuracy, on the first and second days of the experiment, there were no significant main effects for learning mode. On the third day, a significant main effect for learning mode was observed, $t_3(38) = -2.78$, $df_3 = 38$, $p_3 = 0.01$, $d = 0.87$, indicating that handwriting learning had a higher accuracy rate than visual learning.

The results of reaction time for the tasks indicate a significant difference between visual learning and handwriting learning on the first and third days. On both days, the reaction time for visual learning was significantly higher than that for handwriting learning. On the first day, $t_1(38) = -2.43$, $p_1 = 0.02$, $d = 0.77$, and on the third day, $t_3(38) = -2.37$, $p_3 = 0.02$, $d = 0.75$ (Table 6).

3.4. Summary of experimental results for three tasks

In terms of accuracy, significant differences in learning mode were observed on different days: on the first day, differences were significant in the word sound matching task, on the second day in the word meaning matching task, and on the third day in the word form judgment task. This suggests that in terms of accuracy, handwriting's influence on word sound, meaning, and form occurs in the order of sound, meaning, and form. Regarding response time, a significant difference in learning mode was observed in the word form judgment task on the first day. When considering both accuracy and response time, it indicates that the order of influence of handwriting on word sound, form, and meaning is in the sequence of form, sound, and meaning.

4. Discussion

In this study, we compared handwriting with visual learning and conducted three tasks—word form judgment, word sound matching, and word meaning matching—over three consecutive days to assess the advantage of handwriting in word learning. The results demonstrate that handwriting is more advantageous for word learning compared to visual learning. This advantage is evident not only in word form learning but also in word sound and meaning. Furthermore, although handwriting exhibits advantages in word form, sound, and meaning, the sequence of its effects on these aspects differs. Combining the results of correct rates and response times from the three tasks over three days reveals that handwriting primarily influences word form and sound before affecting word meaning.

4.1. Handwriting learning is more beneficial for English word acquisition than visual learning (reading only)

This experiment compared handwriting and visual learning over three consecutive days to study the acquisition of word form, pronunciation, and meaning in English. At the end of each day, word form judgment, pronunciation matching, and meaning matching tasks were used to assess word learning. Overall, the results of the three tasks over three consecutive days consistently demonstrated that handwriting learning outperformed visual learning in acquiring word form, pronunciation, and meaning.

Comparing with previous research on handwriting and visual learning of words, it is evident that handwriting has greater advantages in facilitating word recognition and memory (Wiley & Rapp, 2021; Zemlock et al., 2018). The reasons for the existence of handwriting advantages are multifaceted. Firstly, handwriting requires more attention compared to visual learning. When learning how to write a word or letter, individuals need to engage in deep processing. This process involves focusing attention on the pen tip and surrounding text, following the pen's movement traces to complete writing (Mangen, 2014). In contrast, visual learning relies more on discriminating between visual patterns (Longcamp et al., 2005). Secondly, handwriting involves more sensory engagement, including visual, tactile, and kinesthetic senses, whereas visual learning primarily relies on visual input (Fogassi & Gallese, 2004; Guan et al., 2011). Thirdly, handwriting learning allows

Table 4
Summary of 3-day word sound matching accuracy and response time.

Days	Learning Mode	Matching		Non-Matching	
		Accuracy	Response Time	Accuracy	Response Time
1	Visual	0.59 ± 0.03	3091.45 ± 182.68	0.54 ± 0.04	3184.19 ± 133.34
	Handwriting	0.71 ± 0.03	2796.21 ± 182.68	0.06 ± 0.04	2996.87 ± 173.35
2	Visual	0.69 ± 0.04	2597.08 ± 147.01	0.63 ± 0.04	2643.27 ± 119.98
	Handwriting	0.77 ± 0.04	2381.53 ± 147.01	0.72 ± 0.04	2495.7 ± 119.98
3	Visual	0.78 ± 0.04	2264.67 ± 91.78	0.63 ± 0.03	2270.10 ± 117.05
	Handwriting	0.86 ± 0.04	2140.40 ± 91.78	0.74 ± 0.03	2196.20 ± 117.05

Table 5
Summary of 3-day word meaning matching accuracy and response time.

Days	Learning Mode	Matching		Non-matching	
		Accuracy	Response Time	Accuracy	Response Time
1	Visual	0.69 ± 0.05	1667.19 ± 145.82	0.74 ± 0.04	1673.05 ± 96.98
	Handwriting	0.74 ± 0.05	1549.49 ± 145.82	0.74 ± 0.04	1586.58 ± 96.98
2	Visual	0.73 ± 0.03	1418.67 ± 103.51	0.71 ± 0.03	1482.64 ± 126.35
	Handwriting	0.90 ± 0.03	1416.72 ± 103.51	0.76 ± 0.03	1685.00 ± 126.35
3	Visual	0.74 ± 0.04	1181.87 ± 84.89	0.73 ± 0.04	1243.97 ± 77.23
	Handwriting	0.94 ± 0.04	957.34 ± 84.88	0.84 ± 0.04	1124.63 ± 77.23

Table 6
Summary of 3-day word form matching accuracy and response time.

Days	Learning Mode	Accuracy	*t*	p	Response Time	*t*	p
1	Visual	0.66 ± 0.17	0.21	0.84	2404.00 ± 723.14	−2.43	0.02
	Handwriting	0.67 ± 0.14			1927.14 ± 494.66		
2	Visual	0.73 ± 0.10	−0.05	0.96	1921.26 ± 839.94	−1.15	0.26
	Handwriting	0.73 ± 0.12			1658.40 ± 581.05		
3	Visual	0.73 ± 0.16	−2.78	0.01	1766.16 ± 510.77	−2.37	0.02
	Handwriting	0.85 ± 0.11			1391.40 ± 488.70		

for a longer duration of exposure to English words compared to visual learning. When handwriting, learners have the opportunity to observe the shapes and movement traces of letters in words, combined with the action program of handwriting, which enhances word learning. Additionally, a recent explanation for the existence of handwriting advantages is the more detailed visual processing involved. Handwriting requires reproducing visual forms through a series of fine movements, necessitating familiarity with the shapes and movement traces of letters. In contrast, visual learning and typing do not require such detailed visual processing but rather involve visual contact and matching between graphics or characters (Seyll et al., 2020).

Some studies have also compared handwriting with typing, another form of visual learning. The results indicate that adults who frequently type on keyboards experience a decline in arm and hand fine motor skills compared to those accustomed to handwriting (Sülzenbrück et al., 2011). Moreover, handwriting similarly exhibits advantages in word learning compared to typing (Ihara et al., 2021). This is attributed to the simpler motor program involved in typing compared to handwriting, which may lead to underdeveloped sensorimotor skills in many children or adults (Doughty et al., 2013). Furthermore, handwriting provides additional memory traces (Kiefer et al., 2015). During handwriting, such as letters or words, individuals need to clearly understand the shape of each letter and establish a connection between handwriting and movement, while typing does not establish a connection with letter shapes (James & Engelhardt, 2012). This is because typing only requires finding the correct key on the keyboard and pressing it, without the continuity in time and space as in handwriting (Longcamp et al., 2005). However, this study did not compare the learning effects under typing conditions to further investigate the existence and reasons for handwriting advantages, which is an area for improvement in future research.

4.2. *Influence sequence in handwriting-based learning*

It is worth noting that in this study, the timing of handwriting advantages varied across the three tasks. Specifically, in terms of accuracy, the handwriting advantage appeared first in the word sound matching task on the first day; in the meaning matching task, the handwriting advantage began to emerge on the second day; and in the word form judgment task, the handwriting advantage only began to appear on the third day. Regarding reaction time, the handwriting advantage in word form judgment tasks appeared on the first day. Therefore, combining the results of accuracy and reaction time, the influence of handwriting on word form, pronunciation, and meaning primarily manifested as affecting word form and pronunciation first, followed by meaning.

In a study by Li (2014), which compared handwriting and visual learning of Chinese characters, the results showed that differences in character form appeared first, followed by meaning after the second learning session, and pronunciation differences only emerged in the third and fifth sessions. This suggests that handwriting primarily affects the form and meaning of Chinese characters initially, before influencing pronunciation. Guan et al.'s (2011) study also supported this view. In their research, the CTAT program was used to test the Chinese proficiency of 30 participants, comparing the effects of handwriting and reading-only conditions on vocabulary decision tasks, English meaning, and pronunciation tasks. The results showed higher accuracy in vocabulary decision tasks and partial clue recognition tasks under the handwriting condition. In the post-test and character recognition tasks, handwriting was more effective than the reading-only condition, and handwriting was better at associating form with meaning than visual learning.

The influence sequence of handwriting on the form, pronunciation, and meaning of words and characters differs. However, whether writing characters or words, handwriting primarily influences form and pronunciation first. The reason for this is that handwriting provides more visual spatial information, directing most attention to the spatial structure of words during writing, thus affecting form first (Guan & Zhao, 2019). The different sequences may be due to the significant differences in the visual spatial layout and the relationship between sound, form, and meaning between characters and words. Learning words poses a challenge for learners whose native language is Chinese. English belongs to an alphabetic system, where form and sound are closely linked. According to the English orthographic rules, word form usually represents its pronunciation (Zhang & Yang, 2004). Hence, the form and sound are closely associated, explaining why handwriting affects form and sound first. In contrast, Chinese characters belong to a logographic system, where there are no rules for form-sound correspondence, and the structure is more complex compared to English (Zhang & Xing, 2023). As ideographic characters, each radical in Chinese characters has its own meaning, providing information for learning character meanings (Chen et al., 2017). Therefore, for characters composed of radicals and strokes, handwriting can facilitate the connection between form and meaning.

In summary, this study compared the effects of handwriting and visual learning on English word pronunciation, form, and meaning. Through three consecutive days of learning and testing, it was found that handwriting advantages not only exist in character or letter learning but

also in word learning. Additionally, we discovered that handwriting affects the sequence of word form, word sound, and word meaning differently. The limitations of this study should also be noted. Firstly, although we have provided explanations for the existence of handwriting advantages, these reasons are only speculative, and the exact reasons for handwriting advantages have yet to be confirmed in this experiment. Therefore, future research can not only compare handwriting with visual learning but also include other conditions such as typing to verify the specific reasons for handwriting advantages. Secondly, the selection of participants was somewhat limited, as we only chose sixth-grade elementary school students. Whether similar effects exist for students of other age groups remains uncertain, so future research can expand the range of ages of participants.

5. Conclusion

This study has demonstrated the advantages of handwriting in learning word sound, form, and meaning. The reasons for these advantages may be related to factors such as attentional focus, multisensory processing, and detailed visual processing. Additionally, we have found that handwriting affects the sequence of word pronunciation, form, and meaning differently. By comparing with relevant studies on the sequence of Chinese character pronunciation, form, and meaning, we have analyzed that the different sequences between handwriting effects on Chinese characters and words may be related to the orthographic rules in English. Therefore, in practical teaching, while leveraging orthographic rules to help students establish connections between form and sound can be beneficial, it is essential to adopt flexible teaching methods. Teachers should tailor their approach based on students' individual preferences. For example, some students may prioritize understanding word meanings, so providing diverse teaching resources and strategies is crucial to accommodate different learning styles.

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Ethical approval

All experimental procedures in this study were in line with the national ethical standards and the ethical standards of the Declaration of Helsinki, and were approved by the Ethics Committee of the College of Preschool and Primary Education of Shenyang Normal University.

CRediT authorship contribution statement

Yang Ying: Writing – original draft, Conceptualization, Writing – review & editing, Methodology. **Zhang Huixin:** Resources, Validation, Visualization. **Wu Yunxia:** Supervision. **Li Wenhui:** Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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