Revisiting Handwriting Fundamentals Through an Interdisciplinary Framework

Ann Lee Sien Sut1, Lee Lay Wah1, Low Hui Min1, Ooi Siew Chen2

1 School of Educational Studies, Universiti Sains Malaysia, Pulau Pinang, Malaysia
2 Department of Occupational Therapy, Penang General Hospital, Pulau Pinang, Malaysia

Abstract

Handwriting research lies mostly within discipline-specific boundaries, hindering knowledge transfer across disciplines into academic skills instruction in schools. This paper attempts to review the literature on handwriting across the occupational therapy and education disciplines to propose an interdisciplinary conceptual framework to guide research and intervention on handwriting in the Malay language. This cross-disciplinary review revealed four major factors that may influence Malay language handwriting: i) neuromotor development; ii) ergonomic; iii) orthographic and iv) cognitive factors. The sub-factors under these four major factors also are identified. Many of the neuromotor development and ergonomic factors are derived from the occupational therapy discipline, while the education discipline provides most of the information on orthographic and cognitive factors. As orthography influences handwriting, it is necessary to revisit handwriting from the perspective of languages other than English. In conclusion, an interdisciplinary framework of handwriting synthesised from this cross-disciplinary review will stimulate more coordinated and coherent research on handwriting. The Malay language serves as a future case study for research into orthographies in handwriting.

Keywords: handwriting, interdisciplinary framework of handwriting, Malay language handwriting, handwriting fundamentals

Introduction

Alphabetic handwriting is a process of producing or transcribing letters to form words and sentences (1, 2), a process not to be confused with writing or composing. This review focusses on handwriting in the Malay language, which uses the 26 letters of the English alphabet. Handwriting is viewed as a lower mechanical level of writing, whereas the writing process itself is viewed as a higher-level process that involves cognitive comprehension (3). Handwriting research was popular during the 1980s and 1990s within numerous disciplines, such as neurology, psychology, education and linguistics, among others. The extensive studies conducted during that era resulted in a deeper understanding of handwriting, matured assessment methods, interventions and the development of handwriting models (1). However, by the end of the 20th century, with the emergence of typewriting, followed by the rapid development of digital writing technology, the need to learn handwriting was questioned (1).

In this technological era, we produce text in various ways, such as typewriting (keyboarding skills), digital writing (writing with electronic writing devices) and the use of speech-to-text software. Even so, a study by Mueller and Oppenheimer (4) revealed that taking notes in the traditional way is more beneficial than the use of digital devices. They found that taking notes by hand increases retention of factual content and conceptual
Towards an Interdisciplinary Approach to Handwriting Research

Handwriting has been studied quite substantially in various disciplines, particularly in the fields of education, neurodevelopment and occupational therapy. However, most extant studies are discipline-specific and remain within their own boundaries, resulting in a limited transfer of knowledge and skills into academic skills instruction in schools. Furthermore, few studies on handwriting combined perspectives from both the education and allied health (occupational therapy) disciplines. Therefore, this review was conducted to bridge the knowledge gap between education and occupational therapy disciplines, which are involved directly in handwriting problems among schoolchildren. Combining knowledge on handwriting from both fields would help facilitate more well-informed practical diagnosis and intervention to address children’s handwriting problems. In the occupational therapy literature, the emphasis is on acquisition and readiness of handwriting skills, whereas the influence from language characteristics on the handwriting task is almost non-existent. However, educators focus on functional writing and do not emphasise motor development in handwriting. Integration of research knowledge from these disciplines inevitably would generate a better understanding to help occupational therapists and educators address children’s handwriting difficulties.

An additional research evidence also illustrates handwriting’s positive impact on performance across all academic learning types, such as reading, writing and language (1, 3, 8–10). When handwriting becomes automatic (effortless), writers can focus on composing and writing essays (1, 3). Handwriting also improves letter-recognition skills in reading and, therefore, language recognition itself (8). Handwriting difficulties also can be related in a statistically significant way to academic failure (11), considering that handwriting tasks account for 30%–60% of school activities in elementary school (12).

Handwriting is a complex task in which low- and high-level processes constantly are interacting (13, 14). ‘Low-level process’ entails execution of handwriting production, which involves neuromotor and ergonomic skills, whereas ‘high-level process’ refers to cognitive processes involved in handwriting. ‘Neuromotor skills’ refer to visual-motor integration (VMI), fine motor skills and gross motor ability, while ‘ergonomic skills’ refer to pencil-and-paper manipulation, such as gripping a pencil, positioning a pencil and paper, the consistency of pencil grip and pencil position. Cognitive processes entail working memory, long-term memory and executive attention. As these factors generally are studied independently, a better understanding of the relationships among them in the context of handwriting among struggling learners is needed to produce more efficient interventions. Handwriting skills are a prerequisite of the writing process, as poor handwriting skills directly influence this process by causing cognitive overload (15–19). Thus, proficient writing relies on well-developed handwriting skills (2, 20).

Initial searches were conducted in the EBSCOhost and Scopus databases using the keywords identified from a definition of ‘handwriting’ (‘handwriting’, ‘neuromotor’, ‘fine motor’, ‘handwriting legibility’, ‘handwriting speed’, ‘orthographic coding’ and ‘cognitive’). The abstracts from these papers were scanned, and the most relevant papers from the frequently cited education and occupational therapy disciplines were distilled. These papers were reviewed, further citations from them were identified and checked out, and the process was repeated — a systematic literature review method known as snowballing (21). The review results from both disciplines are integrated and discussed below.

Review Article | Interdisciplinary framework of handwriting

understanding. Note-taking also encourages a more cognitive processes, thereby contributing to effective learning. Mangen et al. (5) found that handwriting helped with word retrieval more than typewriting on conventional and touch keyboards. Another study comparing learning through tablets with the traditional method also suggested that not employing the latter might deprive children of fine motor skills (6). Handwriting also has been found to be important for letter processing in the brain (7). In a functional magnetic resonance imaging study, James and Engelhardt (8) detected stimulation in the brain’s reading circuit among 5-year-old children while they were handwriting, an effect not found after a typing or tracing experience. These studies provide evidence of the importance of producing letters by hand, even in the technological era.

An additional research evidence also illustrates handwriting’s positive impact on performance across all academic learning types, such as reading, writing and language (1, 3, 8–10). When handwriting becomes automatic (effortless), writers can focus on composing and writing essays (1, 3). Handwriting also improves letter-recognition skills in reading and, therefore, language recognition itself (8). Handwriting difficulties also can be related in a statistically significant way to academic failure (11), considering that handwriting tasks account for 30%–60% of school activities in elementary school (12).

Handwriting is a complex task in which low- and high-level processes constantly are interacting (13, 14). ‘Low-level process’ entails execution of handwriting production, which involves neuromotor and ergonomic skills, whereas ‘high-level process’ refers to cognitive processes involved in handwriting. ‘Neuromotor skills’ refer to visual-motor integration (VMI), fine motor skills and gross motor ability, while ‘ergonomic skills’ refer to pencil-and-paper manipulation, such as gripping a pencil, positioning a pencil and paper, the consistency of pencil grip and pencil position. Cognitive processes entail working memory, long-term memory and executive attention. As these factors generally are studied independently, a better understanding of the relationships among them in the context of handwriting among struggling learners is needed to produce more efficient interventions. Handwriting skills are a prerequisite of the writing process, as poor handwriting skills directly influence this process by causing cognitive overload (15–19). Thus, proficient writing relies on well-developed handwriting skills (2, 20).

Initial searches were conducted in the EBSCOhost and Scopus databases using the keywords identified from a definition of ‘handwriting’ (‘handwriting’, ‘neuromotor’, ‘fine motor’, ‘handwriting legibility’, ‘handwriting speed’, ‘orthographic coding’ and ‘cognitive’). The abstracts from these papers were scanned, and the most relevant papers from the frequently cited education and occupational therapy disciplines were distilled. These papers were reviewed, further citations from them were identified and checked out, and the process was repeated — a systematic literature review method known as snowballing (21). The review results from both disciplines are integrated and discussed below.

Towards an Interdisciplinary Approach to Handwriting Research

Handwriting has been studied quite substantially in various disciplines, particularly in the fields of education, neurodevelopment and occupational therapy. However, most extant studies are discipline-specific and remain within their own boundaries, resulting in a limited transfer of knowledge and skills into academic skills instruction in schools. Furthermore, few studies on handwriting combined perspectives from both the education and allied health (occupational therapy) disciplines. Therefore, this review was conducted to bridge the knowledge gap between education and occupational therapy disciplines, which are involved directly in handwriting problems among schoolchildren. Combining knowledge on handwriting from both fields would help facilitate more well-informed practical diagnosis and intervention to address children’s handwriting problems. In the occupational therapy literature, the emphasis is on acquisition and readiness of handwriting skills, whereas the influence from language characteristics on the handwriting task is almost non-existent. However, educators focus on functional writing and do not emphasise motor development in handwriting. Integration of research knowledge from these disciplines inevitably would generate a better understanding to help occupational therapists and educators address children’s handwriting difficulties.
In the education discipline, handwriting research has decreased as the focus has shifted to process writing, which de-emphasises handwriting (1, 22). According to Hayes and Berninger (23), handwriting is influenced mainly by orthography and phonology (letter shapes and sounds, respectively), whereas occupational therapists believe it is predominantly a motor-related skills issue (24).

Students are expected to master handwriting when they start school to partake in learning activities at school that largely involve fine motor skills (e.g., handwriting, cutting and drawing). Children in Malaysian national primary schools with the Malay language as their medium of instruction are expected to have general handwriting proficiency (the ability to hold and write with a pencil correctly, some mastery of alphabetic letters, an understanding of the concept of writing from left to right, etc.), including the ability to use handwriting to complete homework and exams. However, handwriting is not taught formally at national primary schools, leading to poor handwriting performance (legibility and speed), which might affect academic achievement (1). Graham (20) found that students’ handwriting legibility influences teachers’ assessment of their performance, i.e., students with poor handwriting legibility were found to score lower compared with those with legible handwriting despite the content of their written work. Slowness in handwriting also might lead to inability to complete writing tasks on time. These problems also are reflected in the Malaysian primary schools (25), thereby eliciting the authors’ interest in investigating Malay language handwriting in the present study. Furthermore, the Malay language’s unique characteristics add to this study’s value. The Malay language is one of the most highly consistent and transparent of alphabetic orthographies (26), which justifies an investigation, considering that extant research on handwriting mostly has focussed on opaque English language orthography. In a widely adopted practice in many countries, schoolteachers identify and refer students with handwriting problems to an occupational therapist for handwriting intervention (27, 28). The occupational therapist examines the student’s handwriting ability based on knowledge in their discipline (underlying deficits such as fine motor, postural motor, sensory integration, sensorimotor, perceptual and/or behavioural elements, etc.) (29).

Occupational therapists in Malaysia are trained in handwriting intervention and are particularly in demand among stakeholders of children with special needs (e.g., special-education teachers and parents). However, the lack of occupational therapists in South-Asian countries such as Malaysia (30) inevitably has resulted in a serious gap between needs and services. Therefore, a need exists to promote knowledge transfer across disciplines and make intensive clinical interventions over handwriting difficulties more available to general and special-education students in both special and inclusive classrooms (31).

This paper attempts to review relevant literature on handwriting across the occupational therapy and education disciplines to propose an interdisciplinary conceptual framework to guide future research and intervention on handwriting in the Malay language.

The Malay Language’s Influence on Handwriting

Language plays an important role in handwriting (32). For example, each language’s grammatical rules dictate words’ letter arrangements. In addition, phoneme-grapheme correspondence and the number of syllables in a word can affect handwriting speed (33, 34). The grapheme and syllable also modulate the timing of motor production during handwriting skills acquisition. Kandel et al.’s (33) study on handwriting of two-syllable words found that the first syllable is produced grapheme-by-grapheme whereas the second syllable is produced as a whole unit and not grapheme-by-grapheme. Furthermore, knowledge of grapheme-phoneme correspondence (GPC) helps with retrieval of information stored in working memory.

Many previous handwriting studies have focussed on the English language, with some studies examining other languages, such as Chinese (35), Hebrew (36) and Urdu (37). However, handwriting research in the Malay language, the national language of Malaysia, is seriously lacking.

Although the Malay language uses the 26 letters of the English alphabet, there are differences in orthographic transparency and granularity. First, the Malay language is more transparent than the English language, in that grapheme-phoneme mappings are almost perfect. In addition, multi-letter
graphemes are limited in Malay (26, 30, 38). The Malay language is also predominantly bi- and multi-syllabic (39, 40); therefore, revisiting handwriting fundamentals from the Malay language perspective is warranted, as Malay orthography’s transparency can inform handwriting issues in other orthographies with similar characteristics.

In other words, the Malay language’s unique characteristics add to this study’s value. The Malay language is one of the most highly consistent and transparent of orthographies in alphabetic languages (26), warranting investigation, considering that extant handwriting studies have focused mostly on the English language, which is an opaque orthography.

**Handwriting Skills**

Handwriting entails the formation of alphabetic letters by hand, which requires physical motor skills and alphabetic knowledge (41). Handwriting commonly is assessed based on legibility (quality) and speed (fluency) (1, 42, 43). Empirical studies indicate that these two components are not correlated (44, 45). In practice, we can see that legible handwriting can be produced either fluently or slowly; therefore, we can deduce that handwriting speed may not necessarily indicate good or poor handwriting quality. The factors that affect both aspects of handwriting are discussed in the following sections. Generally, both quality and speed improve as the student progresses to higher grades (46).

Handwriting is a process of coordinating multiple modality skills — including fine motor skills, language knowledge and academic readiness — requiring the intertwining of cognitive and motor processes that underlie the handwriting task (13, 43, 47, 48). To produce a text, various processes are initiated — including retrieval of correct letters or words from memory, arrangement of letters in the right order, conversion of phonemes to graphemes to letters, and selection and execution of corresponding motor processes (48) — depending on the handwriting mode (e.g. copying, spelling, dictating).

As the core providers of handwriting remediation and assessments, occupational therapists focus more in-depth on the lower order of writing, comprising neuromotor skills involved in handwriting (29, 43, 49, 50). According to occupational therapists, both intrinsic factors (in-hand manipulation, bilateral integration, motor planning, VMI, visual perception, kinaesthesia, sensory awareness and sustained attention) and extrinsic factors (environmental factors such as lighting, noise, distance when copying, biomechanical ergonomic factors, pencil grip, the writing instrument used, type of paper used and its placement on the desk) affect handwriting (43, 51). These intrinsic and extrinsic factors should be studied to gain a clearer insight on this subject.

Research from the education perspective provides the overall big picture of writing and views handwriting as a process that comprises only lower-level writing skills (52). Hayes and Berninger (23) proposed a cognitive framework for writing that described the comprehensive writing process from the perspective of educational psychology. According to the model (23), handwriting is a lower-level skill in the overall framework of writing, which is positioned in transcription, a subcomponent in the translation process (3). These low-level developmental skills are more important for beginning writers compared with mature ones (53). According to Berninger et al. (3), two lower-level writing processes in the transcription subcomponent (one of the subcomponents in translation; see [15] and [23]) are handwriting and spelling. However, it is worth noting that this review focuses on handwriting fundamentals, which do not include spelling, although both are viewed as lower-level writing processes.

It can be said that knowledge from both disciplines is complementary, so an interdisciplinary conceptual framework for handwriting would benefit teachers, who generally are not familiar with knowledge from the occupational therapy discipline.

**Neuromotor Developmental Factors in Handwriting**

Neuromotor components related to handwriting may include fine motor skills (in-hand manipulation, bilateral integration and motor planning), VMI, visual perception, kinaesthesia and proprioception, sensory modalities and sustained attention (29, 42). Most studies on handwriting-related motor developments focus on VMI, fine motor skills
and gross motor ability, which are important in the development of the ability to control a writing tool, thereby allowing for good handwriting (27, 29, 54, 55).

**Visual-Motor Integration**

VMI plays a prominent role in the copying task. When a child copies a word or sentence from a source, the child visualises the letter form, assigns meaning to it, manipulates the writing tool with motor control and eventually produces the written work (29).

VMI refers to the ability to coordinate visual information with a motor response and is the best predictor of handwriting legibility (14, 29, 42, 48–50, 56–58). VMI is tested widely using the Beery-Buktenica Developmental test of VMI (59). VMI in the Beery-Buktenica Developmental test is assessed by drawing simple or complex geometric forms.

On the other hand, the influence of visual perception (the ability to make sense of what is seen) on handwriting is unclear (56, 60, 61). Research on hand-eye coordination also has not indicated a strong relationship with handwriting (24, 29). However, Kaiser et al.’s (62) findings demonstrated that hand-eye coordination associated with VMI predicts handwriting quality.

**Fine Motor Skills**

Fine motor skills in handwriting refer to finger movements coordinated with muscle movements in the wrist, elbow and shoulder to control a writing tool to produce text or writing (12, 29, 60, 63). Fine motor skills are related closely to handwriting (28, 29, 48, 54–56). According to Dinehart (64), early fine motor skills may even be useful in determining readiness for school. Many occupational therapists incorporate fine motor skills in their assessment of and interventions with clients who have handwriting difficulties (28, 29, 42, 43, 64, 65). Four fine motor skills that are correlated significantly with handwriting are identified, namely, as i) in-hand manipulation (finger functions); ii) fine motor precision; iii) manual dexterity and iv) motor planning.

In-hand manipulation (3, 14, 29, 43, 50, 55, 56, 65, 66) refers to the process of adjusting objects within the hand (54). During handwriting, the writer moves a writing tool with fingers and adjusts it to write. Some researchers have described in-hand manipulation as finger functions in handwriting studies (14, 67). In-hand manipulation may be examined through the fingers’ rotation, shift and translation (29, 54). Berninger and Rutberg (67) found that a finger succession task was the best predictor of handwriting and writing skills among other five-finger tasks used in their study. They suggested that the finger succession task was also the best measure of motor planning. Motor planning in handwriting is the ability to plan, sequence and execute letters in words (42), and it is correlated positively with handwriting legibility (29).

During handwriting tasks, the student stabilises the writing paper with their nonwriting hand, demonstrating bilateral integration ability, which is correlated with handwriting (29, 43, 45). Fine motor skills, such as motor precision and high-coordination (dexterity) when using a writing tool, also were found to be correlated positively with handwriting tasks (29, 50, 55, 68).

**Gross Motor Skills**

Gross motor skills mainly refer to postural control during handwriting tasks (69). Body posture influences the efficiency of handwriting production (45) because the trunk’s stability allows the writer to adjust their posture to accomplish tasks that require fine motor skills, such as handwriting (60). Cheng et al.’s (70) study further confirmed that lower body stabilisation was important in providing support to the body during writing for children with cerebral palsy.

According to Erhardt and Meade (60), good posture entails:

“...sitting with hips at 90° angle and feet stabilised on the floor, good pelvic and spinal alignment, cervical control for downward visual gaze and shoulder integrity for arm and hand control” (p. 199).

Studies by Blote et al. (71) and Sassoon et al. (72) found a weak correlation between writing posture and handwriting quality, but a strong correlation between writing posture and handwriting speed (63, 69).

Kinaesthesia is the awareness of movements in our body, and proprioception is the sense through which we perceive the position of joints in our body (73). Cornhill and Case-Smith (29) relate kinaesthesia to the level of pressure applied to the writing tool, and the ability to write within boundaries. Kinaesthesia
has demonstrated a significant correlation with handwriting legibility (29, 74). Schneck (74) found that kinaesthesia influences handwriting by influencing pencil grip, but Tseng and Murray (49) reported conflicting results. The proprioception sense did not correlate to writing legibility (75), but Schneck (74) found a possible relationship between children’s pencil grip and proprioception.

**Ergonomic Factors**

Ergonomic factors also play an important role in handwriting performance (36, 45, 63, 76), but they have received less attention (36). Ergonomic factors relate to the design of certain tools, machines, systems, tasks, jobs and environments to optimise them for human use (45). The ergonomic factors in handwriting include pencil grip, the positioning of pencil and paper, consistency of pencil grip and pencil position, and pressure applied to the writing tool. Many occupational therapists focus on pencil grip in their intervention (42), as they believe that immature pencil grip may result in difficulty controlling finger movements while writing (43). Extant research has found that most poor writers possess an immature pencil grip (74, 77), but other studies also have demonstrated that pencil grip is not related to handwriting legibility and speed (36, 50, 63, 76). Only one study, by Schneck (74), found a positive relation between handwriting and pencil grip.

Pencil positioning and pencil grip consistency also are correlated highly to handwriting (36, 45). In addition, Parush et al. (45) reported other correlated ergonomic factors, including pressure consistency and paper positioning. However, it should be noted that although these ergonomic factors are associated with handwriting, no causal relationships have been established (45).

A notable study by Dennis and Swinth (78) examined the relationship between handwriting endurance and pencil grip and found that pencil grip did not affect task endurance, but that task length affected handwriting legibility.

**Orthographic Factors**

Orthography is the graphic representation of spoken language, and graphic forms in alphabetic orthography contain phonological units (79). Three orthographic effects that are related to handwriting have been identified — letter knowledge, orthographic coding and syllable-size processing units — so it would be relevant to include these orthographic effects in the Malay language handwriting conceptual framework.

**Letter Knowledge**

According to Fears and Lockman (80), letter recognition influences early handwriting. Letter knowledge refers to children’s familiarity with letter shapes, names and corresponding phonemes (81). Piasta and Wagner (82) presented five letter knowledge outcomes, namely: i) letter-name knowledge; ii) letter-sound knowledge; iii) letter-name fluency; iv) letter-sound fluency and v) letter writing. Letter-name knowledge and letter writing are highly correlated (83). Children need to learn the letters in the alphabet before they can start to learn writing.

**Orthographic Coding**

Berninger et al. (84) defined orthographic coding as retrieving letter forms from memory to write. Berninger et al. (84) administered a modified orthographic coding task to children in each grade to examine the ability to retrieve orthography from memory. The children needed to identify whether a previously shown card contained a whole word, single letter or letter cluster. Beginning writers require the ability to store and retrieve a single letter, a cluster of letters or a whole word from memory during writing; therefore, automatisation of orthographic (letter, cluster and word) coding/retrieval from memory will increase handwriting speed (58). The findings from Berninger et al.’s study (84) also revealed a pattern as to how children progress from relying on whole word coding to letter and letter cluster coding as they begin to grasp GPC knowledge. The error analysis from orthographic coding tasks suggested that orthography-phonology correspondence may be related to orthographic coding. On the other hand, Weintraub and Graham’s study (14) did not find a correlation between orthographic processes (letter writing, orthographic speed test, expressive orthographic coding) and handwriting legibility.

**Syllable-Size Processing Units**

Kandel et al. (33) found consistent dysfluency at the grapheme and syllable boundary in French children’s handwriting.
phonetically, but bi-syllabic orthographically, and words that are bi-syllabic both phonetically and orthographically. Their findings indicated that children use orthographic, rather than phonological syllables as processing units to plan words mentally before they write.

In addition, the syllable structure was found to constrain motor production in handwriting within both French and Spanish orthographies (89). Lambert et al. (34) examined the writing of two- to four-syllable words and nonwords among adults and found that during the nonword task, syllable-size chunks were observed. According to Graham et al. (11), the act of chunking the letter into syllable-size processing units reduces attention and memory demands, thereby allowing for higher-level writing processes (11).

Cognitive Factor

According to Hayes and Berninger (23), writing requires several cognitive components that operate at different levels during the writing and composing processes. Three cognitive components involved in handwriting are identified from the literature, namely working memory, long-term memory and executive attention or working memory capacity (18, 19, 23, 43, 53, 90–96). These cognitive factors closely interact during performance of complex tasks, such as handwriting.

During transcription (translating language presentations into written words), substantial attention is required. In this process, working memory retrieves related information (e.g. letter forms, letter sequences, letter writing,
etc.) from long-term memory and maintains the information until handwriting is executed (97). Figure 1 illustrates the connections between working memory, attention (working memory capacity) and long-term memory (98).

**Working Memory**

Handwriting is a complex task that requires working memory (19), which is a temporary platform for storing, processing and retrieving information from long-term memory (53, 90, 93, 95). Typically, the terms ‘working memory’ and ‘short-term memory’ are used ambiguously in extant studies, and even interchangeably in many studies (99). Although there is overlap between both terms, as they share similarities, it depends on the task studied. However, ‘working memory’ is used instead of ‘short-term memory’ in this handwriting literature review because handwriting involves manipulation of information stored in the temporary platform for further processing.

**Long-Term Memory**

According to Berninger et al. (17), handwriting not only involves the generation of letter representations in memory, but also retrieval of representations from memory. Therefore, poor memory impedes retrieval of letter forms from memory (100). Long-term memory functions as storage for information, and its duration and storage capacity is unlimited (98). The more knowledge writers possess in their long-term memory, the better their writing quality and fluency (23). In developing handwriting skills, a beginner will retrieve letter knowledge (in this case, alphabet letters) from long-term memory.

**Executive Attention (Working Memory Capacity)**

Just and Carpenter (18) proposed a capacity model of working memory that was found to fit writing acquisition (96). Handwriting may strain working memory’s processing capacity, especially among beginning writers, because of its complex processes that involve the writer’s neuromotor development and the language’s orthographic characteristics (18, 89, 101).

Olive (101), in his review, presented an integrated model of the coordination of the writing process (cascading and parallel), which clearly communicated how working memory capacity affects coordination of the writing process. This also was demonstrated in Kandel et al.’s extensive research (33, 34, 85, 87–89) on the syllable processing units mentioned previously.

The central executive in Baddeley and Hitch’s model of working memory in 1974 (90) presents a function that resembles working memory capacity, as it governs the working memory system by allocating attention within working memory (e.g. distributing attention between multiple tasks), allowing for simultaneous input from different types of sensory information.

In addition, the executive function was found to be correlated highly with attentional control (91): ‘Attentional control has been conceptualised as executive functioning by neuropsychologists and as working memory capacity by experimental psychologists’ (94, p.1). Findings from McCabe et al. (94) suggest merging working-memory capacity with executive function as executive attention, considering that they both represent similar attentional control in performing complex tasks.

Therefore, working memory resources (attention) are shared among various processes involved in a task (19, 95, 96). An overload in working memory during handwriting tasks reduces retrieval performance, as attention is focussed on planning and performing motor components (19). This approach emphasises the role of automatisation of low-level processes, which free up capacity for high-level processes (95). Upon achieving automatisation of low-level skills in handwriting, writers can focus on high-level processes (1, 19, 53). Studies have demonstrated that the automatisation of handwriting progresses with grades and age (1, 3, 53, 102).

The Malay language’s bi- and multi-syllabic language characteristic might pose a challenge to writers, as a higher demand on executive attention is necessary (19). A three-syllable word, which is common in the Malay language, is longer than three-syllable English words. Therefore, rehearsal is needed to maintain these syllables in working memory and to avoid information decay of the syllables (30, 31). Although the high transparency and consistency of phoneme-grapheme correspondences in the Malay language may reduce some demand on attention resources and facilitate recall of motor production during handwriting preparation, constant rehearsal processes are needed to maintain multiple syllabic Malay words in working memory. We believe that the need to
occupational therapy discipline, whereas the education discipline provides most of the information on linguistic and memory factors. Neuromotor development factors include VMI, fine motor skills (in-hand manipulation, motor planning, bilateral integration, motor precision and hand coordination) and gross motor skills. Ergonomic factors primarily comprise types of pencil grip, pencil grip consistency and pencil positioning. Orthographic factors include letter knowledge, orthographic coding and syllable-size processing units. Finally, cognitive factors include working memory, long-term memory and executive attention. The primary knowledge sources of these four major handwriting factors are mapped and provided in Figure 2.

These four main factors are likely to contribute to individual differences in the Malay language handwriting process. An interdisciplinary framework that links knowledge between the two disciplines is presented in Table 1 and will provide a more coordinated and coherent reference to stimulate future handwriting research. From this framework, it is hypothesised that Malay language handwriting fundamentals comprise four major factors, along with sub-factors. Next, empirical research will be needed to reveal the actual factor structure of Malay language handwriting, each factor’s unique contributions to Malay language handwriting and the interlinkages among these factors and handwriting.
**Table 1.** An interdisciplinary conceptual framework of Malay language handwriting

| Task                        | Factors           | Sub-factors                                      |
|-----------------------------|-------------------|--------------------------------------------------|
| Handwriting (legibility and speed) | Neuromotor development | VMI                                               |
|                             | Fine motor        | In-hand manipulation                             |
|                             |                   | Motor planning                                   |
|                             |                   | Motor precision and dexterity                    |
|                             |                   | Bilateral integration                            |
|                             | Gross motor       | Postural control                                 |
| Ergonomic                   | Pencil grip       |                                                  |
|                             |                   | Pencil and paper positioning/consistency         |
| Orthography                 | Letter knowledge  |                                                  |
|                             | Orthography coding|                                                  |
|                             | Syllable-size processing unit |          |
| Cognitive                    | Working memory    |                                                  |
|                             | Long-term memory  |                                                  |
|                             | Executive attention (working memory capacity) |      |

**Conclusion**

This study proposed an interdisciplinary conceptual framework on Malay language handwriting to spotlight handwriting’s importance in academic competency. This framework will help develop empirical studies to answer pertinent questions about Malay language handwriting fundamentals, and these answers will form the basis for the design and development of assessment and intervention methods to address handwriting difficulties, to be applied by teachers as Tier 1 and Tier 2 interventions in inclusive classrooms. Finally, this paper spotlights orthography’s overlooked role in handwriting. The Malay language served as a case study for research into handwriting orthographies.

**Acknowledgements**

This work is supported by the Malaysian Ministry of Education Fundamental Research Grant Scheme.

**Conflict of Interest**

None.

**Funds**

Grant No.: FRGS/1/2018/SSI09/USM/01/1 (203/PGURU/6711710.

**Authors’ Contributions**

Conception and design: ALSS, LLW, LHM, OSC
Drafting of the article: ALSS, LLW
Critical revision of the article for important intellectual content: LLW, LHM, OSC
Final approval of the article: ALSS, LLW, LHM, OSC

**Correspondence**

Professor Dr Lee Lay Wah  
M Ed (USM), PhD (UKM)  
School of Educational Studies,  
Universiti Sains Malaysia,  
11800 USM, Pulau Pinang, Malaysia.  
Tel: +604 653 5191  
Fax: +604 657 2907  
E-mails: lwah@usm.my, mydyslexia@gmail.com
References

1. Graham S, Weintraub N. A review of handwriting research: progress and prospects from 1980 to 1994. Educ Psychol Rev. 1996;8:7–87. https://doi.org/10.1007/BF01761831

2. Myers CA. A fine motor program for preschoolers. In: Henderson A, Pehoski C, editors. Hand function in the child: foundations for remediation. 2nd ed. St. Louis (MO): Mosby/ Elsevier; 2006. pp. 267–288. https://doi.org/10.1016/B978-032303186-8.50016-2

3. Berninger V, Yates C, Cartwright A, Rutberg J, Remy E, Abbott R. Lower-level developmental skills in beginning writing. Read Writ. 1992;4:257–280. https://doi.org/10.1007/BF01027151

4. Mueller PA, Oppenheimer DM. The pen is mightier than the keyboard: advantages of longhand over laptop note taking. Psychol Sci. 2014;25(6):1159–1168. https://doi.org/10.1177/0956797614524581

5. Mangen A, Anda LG, Oxborough GH, Brønnick K. Handwriting versus keyboard writing: effect on word recall. J Writ Res. 2015;7(2):227–247. https://doi.org/10.17239/jowr-2015.07.02.1

6. Lin LY. Differences between preschool children using tablets and non-tablets in visual perception and fine motor skills. Hong Kong J Occup Ther. 2019;32(2):118–126. https://doi.org/10.1177/1569186119888698

7. James KH. Sensori-motor experience leads to changes in visual processing in the developing brain. Dev Sci. 2010;13(2):279–288. https://doi.org/10.1111/j.1467-7687.2009.00883.x

8. James KH, Engelhardt L. The effects of handwriting on functional brain development in pre-literate children. Trends Neurosci Educ. 2012;1(1):32–42. https://doi.org/10.1016/j.tine.2012.08.001

9. Cameron CE, Brock LL, Murrah WM, Bell LH, Wozalla SL, Grissmer D, et al. Fine motor skills and executive function both contribute to kindergarten achievement. Child Dev. 2012;83(4):1229–1244. https://doi.org/10.1111/j.1467-8624.2012.01768.x

10. Graham S, Harris K. The role of self-regulation and transcription skills in writing and writing development. Educ Psychol. 2000;35(1):3–12. https://doi.org/10.1207/S15326985EP3501_2

11. Graham S, Harris K, Fink B. Is handwriting causally related to learning to write? Treatment of handwriting problems in beginning writers. J Educ Psychol. 2000;92(4):620–633. https://doi.org/10.1037/0022-0663.92.4.620

12. McHale K, Cermak S. Fine motor activities in elementary school: preliminary findings and provisional implications for children with fine motor problems. Am J Occup Ther. 1992;46(10):898–903. https://doi.org/10.5014/ajot.46.10.898

13. Van Galen GP. Handwriting: issues for a psychomotor theory. Hum Mov Sci. 1991;10(2–3):165–191. https://doi.org/10.1016/0167-9457(91)90003-G

14. Weintraub N, Graham S. The contribution of gender, orthographic, finger function, and visual-motor processes to the prediction of handwriting status. Occup Ther J Res. 2000;20(2):121–141. https://doi.org/10.1177/153944920002000203

15. Berninger VW. Coordinating transcription and text generation in working memory during composing: automatic and constructive processes. Learn Disabil Q. 1999;22(2):99–112. https://doi.org/10.2307/1511269

16. Berninger VW, Vaughan K, Abbott RD, Brooks A, Abbott SP, Rogan L, et al. Early intervention for spelling problems: teaching functional spelling units of varying size with a multiple-connections framework. J Educ Psychol. 1997;89(4):652–666. https://doi.org/10.1037/0022-0663.89.4.652

17. Berninger VW, Vaughan K, Abbott RD, Abbott SP, Rogan LW, Brooks A, et al. Treatment of handwriting problems in beginning writers: transfer from handwriting to composition. J Educ Psychol. 1997;89(4):652–666. https://doi.org/10.1037/0022-0663.89.4.652

18. Just M, Carpenter P. A capacity theory of comprehension: individual differences in working memory. Psychol Rev. 1992;99(1):122–149. https://doi.org/10.1037/0033-295X.99.1.122
19. Tindle RF. Handwriting and working memory: the role of memory and other cognitive factors in the performance of psychomotor skills such as handwriting and drawing. PhD thesis. Southern Cross University; 2016. https://epubs.scu.edu.au/theses/554/

20. Graham S. Handwriting instruction: a commentary on five studies. Read Writ. 2018;31(4):1–11. https://doi.org/10.1007/s11145-018-9854-5

21. Wohlin C. Guidelines for snowballing in systematic literature studies and a replication in software engineering. 18th International Conference on Evaluation and Assessment in Software Engineering (EASE '14); 2014 May 13–14; London, England, BC, United Kingdom: Association for Computing Machinery; vol. 38. pp. 1–10. https://doi.org/10.1145/2601248.2601268

22. Graham S, Harris KR. The effects of whole language on children’s writing: a review of literature. Educ Psychol. 1994;29(4):187–192. https://doi.org/10.1207/s15326985ep2904_2

23. Hayes JR, Berninger VW. Cognitive processes in writing: a framework. In: Arfe B, Dockrell J, Berninger VW, editors. Writing development and instruction in children with hearing, speech, and language disorders. New York: Oxford University Press; 2014. pp. 3–15.

24. Tseng MH, Cermak SA. The evaluation of handwriting in children. Sensory Integ Q. 1991;19(4):3–6.

25. Lau PK. Kesan senaman brain gym terhadap tahap kekemasan tulisan bahasa Cina murid-murid tahun lima. Jurnal Penyelidikan Tindakan IPG KBL. 2010;4:23–40.

26. Lee LW. Development and validation of a reading-related assessment battery in Malay for the purpose of dyslexia assessment. Annals of Dyslexia. 2008;58:37–57. https://doi.org/10.1007/s11881-007-0011-0

27. Alston J, Taylor J. Handwriting: theory, research and practice. New York (NY): Nichols Publishing Company; 1987.

28. Feder K, Majnemer A, Synnes A. Handwriting: current trends in occupational therapy practice. Can J Occup Ther. 2000;67(3):197–204. https://doi.org/10.1177/000841740006700313

29. Cornhill HE, Case-Smith J. Factors that relate to good and poor handwriting. Am J Occup Ther. 1996;50(9):732–739. https://doi.org/10.5014/ajot.50.9.732

30. Lee LW, Low HM. The evolution of special education in Malaysia. British J Spec Educ. 2014;41(1):42–58. https://doi.org/10.1111/1467-8578.12048

31. Fuchs D, Fuchs LS. Rethinking service delivery for students with significant learning problems: developing and implementing intensive instruction. Remedial Spec Educ. 2015;36(2):105–111. https://doi.org/10.1177/0741932514558337

32. Ziviani J, Wallen M. The development of graphomotor skills. In: Henderson A, Pehoski C, editors. Hand function in the child: foundations for remediation. 2nd ed. St. Louis, (MO): Mosby; 2006. pp. 217–236. https://doi.org/10.1016/B978-032303186-8.50014-9

33. Kandel S, Soler O, Valdois S, Gros C. Graphemes as motor units in the acquisition of writing skills. Read Writ. 2006;19:313–337. https://doi.org/10.1007/s11145-005-4321-5

34. Lambert E, Kandel S, Fayol M, Esperet E. The effect of the number of syllables when writing poly-syllabic words. Read Writ. 2008;21:859–883. https://doi.org/10.1007/s11145-007-9095-5

35. Poon K, Li-Tsang C, Weiss T, Rosenblum S. The effect of a computerized visual perception and visual-motor integration training program on improving Chinese handwriting of children with handwriting difficulties. Res Dev Disabilities. 2010;31(6):1552–1560. https://doi.org/10.1016/j.ridd.2010.06.001

36. Rosenblum S, Goldstand S, Parush S. Relationships among biomechanical ergonomic factors, handwriting product quality, handwriting efficiency, and computerized handwriting process measures in children with and without handwriting difficulties. Am J Occup Ther. 2006;60(1):28–39. https://doi.org/10.5014/ajot.60.1.28

37. Jameel HT, Nabeel T. Effect of visual-motor integration training on legibility of Urdu handwriting. Pakistan J Educ. 2017;34(1):81–94.
38. Lee LW. Design and development of a Malay word recognition intervention program for children with dyslexia. Aust J Learning Difficulties. 2019;24(6):1–17. https://doi.org/10.1080/1940158.2019.1661261

39. Lee LW, Low HM, Abdul Rashid. A comparative analysis of word structures in Malay and English storybooks. Pertanika J Soc Sci Human. 2013;21(1):67–84.

40. Winskel H, Lee LW. Learning to read and write in Malaysian/Indonesian: a transparent alphabetic orthography. In: Winskel H, Padakannay P, editors. South and Southeast Asian psycholinguistics. Cambridge: Cambridge University Press; 2014. pp. 179–183. https://doi.org/10.1017/CBO9781139084642.020

41. Datchuk S. Teaching handwriting to elementary students with learning disabilities: a problem-solving approach. Teach Except Child. 2015;48(1):19–27. https://doi.org/10.1177/004005915594782

42. Amundson SJ. Evaluation tools of children’s handwriting (ETCH). Homer, AL: O.T. KIDS; 1995.

43. Feder K, Majnemer A. Handwriting development, competency and intervention. Dev Medic Child Neurol. 2007;49(4):312–317. https://doi.org/10.1111/j.1469-8749.2007.00312.x

44. Meulenbroek RGJ, Van Galen GP. Perceptual-motor complexity of printed and cursive letters. J Experiment Educ. 1990;58(2):95–110. https://doi.org/10.1080/00220973.1990.10806527

45. Parush S, Levanon-Erez N, Weintraub N. Ergonomic factors influencing handwriting performance. Work. 1998;11(3):295–305. https://doi.org/10.3233/WOR-1998-11306

46. Graham S, Weintraub N, Berninger VW. The relationship between handwriting style and speed and legibility. J Educ Res. 1998;91(5):290–297. https://doi.org/10.1080/00220679809597556

47. Berninger VW, Abbott RD, Abbott SP, Graham S, Richards T. Writing and reading: connections between language by hand and language by eye. J Learn Disabil. 2002;35(1):39–56. https://doi.org/10.1177/002221940203500104

48. Volman MJM, van Schendel BM, Jongmans MJ. Handwriting difficulties in primary school children: a search for underlying mechanisms. Am J Occup Ther Assoc. 2006;60(4):451–460. https://doi.org/10.5014/ajot.60.4.451

49. Tseng M, Murray E. Differences in perceptual–motor measures in children with good and poor handwriting. Occup Ther J Res. 1994;14(1):19–36. https://doi.org/10.1177/153944929401400102

50. Bazyk S, Michaud P, Goodman G, Papp P, Hawkin E, Welch MA. Integrating occupational therapy services in a kindergarten curriculum: a look at the outcomes. Am J Occup Ther. 2009;63(2):160–171. https://doi.org/10.5014/ajot.63.2.160

51. Tomchek SD, Schneck CM. Evaluation of handwriting. In: Henderson A, Pehoski C, editors. Hand function in the child: foundations for remediation. 2nd ed. (MO): Mosby; 2006. pp. 291–318. https://doi.org/10.1016/B978-032303186-8.50017-4

52. Graham S, Berninger VM, Weuntraub N, Schafer W. Development of handwriting speed and legibility in Grades 1–9. J Educ Res. 1998;92(1):42–52. https://doi.org/10.1080/00220679809597574

53. Berninger VW, Swanson HL. Modifying Hayes & Flower’s model of skilled writing to explain beginning and developing writing. In: Butterfield E editor. Children’s writing: toward a process theory of development of skilled writing. Greenwich (CT): JAI Press; 1994. pp. 57–81.

54. Exner CE. In-hand manipulation skills, In: Case-Smith J, Pehoski C, editors. Development of hand skills in the child. Rockville (MD): American Occupational Therapy Association; 1992. pp. 35–45.

55. Seo SM. The effect of fine motor skills on handwriting legibility in preschool age children. J Phys Ther Sci. 2018;30(2):324–327. https://doi.org/10.1589/jpts.30.324

56. Clark GJ. The relationship between handwriting, reading, fine motor and visual-motor skills in kindergarteners. Master’s thesis. Iowa State University Digital Repository: Iowa State University; 2010. https://lib.dr.iastate.edu/etd/11399
57. Daly CJ, Kelley GT, Krauss A. Relationship between visual-motor integration and handwriting skills of children in kindergarten: a modified replication study. *Am J Occup Ther.* 2003;57(4):459–462. https://doi.org/10.5014/ajot.57.4.459

58. Heidi A, Hinojosa J, Roston KL. Improving a child's writing skills for increased attention to academic activities. *J Occup Ther, Schools, Early Intervention.* 2009;2(3–4):171–177. https://doi.org/10.1080/19411240903392566

59. Beery KE, Buktenica NA, Beery NA. *The Beery-Buktenica developmental test of visual-motor integration: administration, scoring, and teaching manual.* 6th ed. Minneapolis (MN): Pearson; 2010. https://doi.org/10.1037/t48947-000

60. Erhardt RP, Meade V. Improving handwriting without teaching handwriting: the consultative clinical reasoning process. *Aust Occup Ther J.* 2005;52(3):199–210. https://doi.org/10.1111/j.1440-1630.2005.00505.x

61. Tseng MH, Cermak SA. The influence of ergonomic factors and perceptual-motor abilities on handwriting performance. *Am J Occup Ther.* 1993;47(10):919–925. https://doi.org/10.5014/ajot.47.10.919

62. Kaiser ML, Albaret, JM, Doudin PA. Relationship between visual-motor integration, eye-hand coordination, and quality of handwriting. *J Occup Ther, School Early Interven.* 2009;2(2):87–95. https://doi.org/10.1080/1941124090346228

63. Schwellnus H, Carnahan H, Kushki A, Polatajko H, Missiuna C, Chau T. Effect of pencil grasp on the speed and legibility of handwriting after 10-minute copy task in Grade 4 children. *Aust Occup Ther J.* 2012;59(3):180–187. https://doi.org/10.1111/j.1440-1630.2012.01014.x

64. Dinehart LH. Handwriting in early childhood education: current research and future implications. *J Early Childhood Literacy.* 2015;15(1):97–118. https://doi.org/10.1177/1468798414522825

65. Case-Smith J. The relationships among sensorimotor components, fine motor skill, and functional performance in preschool children. *Am J Occup Ther.* 1995;49(7):645–652. https://doi.org/10.5014/ajot.49.7.645

66. Denton PL, Cope S, Moser C. The effects of sensorimotor-based intervention versus therapeutic practice on improving handwriting performance in 6- to 11-year-old children. *Am J Occup Ther.* 2006;60(1):16–27. https://doi.org/10.5014/ajot.60.1.16

67. Berninger VW, Rutberg J. Relationship of finger function to beginning writing: application to diagnosis of writing disabilities. *Dev Med Child Neuro.* 1992;34:155–172.

68. Smits-Engelsmen BC, Niemeijer AS, Van Gelan GP. Fine motor deficiencies in children diagnosed as DCD based on poor grapho-motor ability. *Human Move Sci.* 2001;20(1–2):161–182. https://doi.org/10.1016/S0167-9457(01)00033-1

69. Tayseer Y. Correlation between gross motor activities and hand writing skills in elementary school children. *Trends Appl Sci Res.* 2015;10(5):259–269. https://doi.org/10.3923/tasr.2015.259.269

70. Cheng HY, Lien YJ, Yu YC, JU YY, Cheng CH, Wu DB. The effect of lower body stabilization and different writing tools on writing biomechanics in children with cerebral palsy. *Res Dev Disabilities.* 2013;34(4):1152–1159. https://doi.org/10.1016/j.ridd.2012.12.019

71. Blote A, Zielstra E, Zoetewey M. Writing posture and writing movement of children in kindergarten. *J Human Move.* 1987;13:323–341.

72. Sassoon R, Nimmo-Smith I, Wing AM. An analysis of children's penholds. In: Kao H, van Galen GP, Hoosain R, editors. *Graphonomics: contemporary research in handwriting.* Elsevier Science; 1986. pp. 93–106. https://doi.org/10.1016/S0166-4115(09)60074-1

73. Danzl MM, Wiegand MR. Orthopedic physical therapy secrets. In: Placzek JD, Boyce DA, editors. *Orthopedic neurology.* 3rd ed. Riverport Lane: St. Louis, Missouri; 2017. pp.1103–1133.

74. Schneck CM. Comparison of pencil-grip patterns in first graders with good and poor writing skills. *Am J Occup Ther.* 1991;45(8):701–706. https://doi.org/10.5014/ajot.45.8.701

75. Hong SY, Jung NH, Kim KM. The correlation between proprioception and handwriting legibility in children. *J Physic The Sci.* 2016;28(10):2849–2851. https://doi.org/10.1589/jpts.28.2849
76. Kavak ST, Bumin G. The effects of pencil grip posture and different desk designs on handwriting performance in children with hemiplegic cerebral palsy. J Pediatr (Rio J). 2009;85(4):346–352. https://doi.org/10.2223/JPED.1914

77. Schneck CM, Henderson A. Descriptive analysis of the developmental progression of grip position for pencil and crayon control in nondysfunctional children. Am J Occup Ther. 1990;44(10):893–900. https://doi.org/10.5014/ajot.44.10.893

78. Dennis JL, Swinth Y. Pencil grasp and children’s handwriting legibility during different-length writing tasks. Am J Occup Ther. 2001;55(2):175–183. https://doi.org/10.5014/ajot.55.2.175

79. Frost R. Orthographic systems and skilled word recognition processes in reading. In: Snowling MJ, Hulme C, editors. The science of reading: a handbook. Oxford: Blackwell; 2005. pp. 272–295. https://doi.org/10.1002/9780470757642.ch15

80. Fears NE, Lockman JJ. How beginning handwriting is influenced by letter knowledge: visual-motor coordination during children’s form copying. J Experiment Child Psychol. 2018;171:55–70. https://doi.org/10.1016/j.jecp.2018.04.004

81. Foulin JN. Why is letter-name knowledge such a good predictor of learning to read? Read Writ. 2005;18:129–155. https://doi.org/10.1007/s11145-004-5892-2

82. Piasta SB, Wagner RK. Learning letter names and sounds: effects of instruction, letter type, and phonological processing skill. J Experiment Child Psychol. 2010;105(4):324–344. https://doi.org/10.1016/j.jecp.2009.12.008

83. Molfese V, Beswick J, Molnar A, et al. Alphabetic skills in preschool: a preliminary study of letter naming and letter writing. Dev Neuropsychol. 2006;29(1):5–19. https://doi.org/10.1207/s15326942dn2901_2

84. Berninger V, Yates C, Lester K. Multiple orthographic codes in reading and writing acquisition. Read Writ. 1991;3:115–149. https://doi.org/10.1007/BF00420030

85. Kandel S, Valdois S. Syllables as functional units in a copying task. Language Cogn Processes. 2006;21(4):432–452. https://doi.org/10.1080/01690960400018378

86. Alvarez CJ, Cottrell D, Afonso O. Writing dictated words and picture names: syllabic boundaries affect execution in Spanish. Appl Psycholinguist. 2009;30(2):205–223. https://doi.org/10.1017/S0142716409090092

87. Kandel S, Alvarez CJ, Vallee N. Morphemes also serve as processing units in handwriting production. In: Baciu M, editor. Neuropsychology and cognition of language behavioural, neuropsychological and neuroimaging studies of spoken and written language. Kerala, India: Research Signpost; 2008. pp. 87–100.

88. Kandel S, Herault L, Grosjacques G, et al. Orthographic vs. phonologic syllables in handwriting production. Cognitive. 2009;110(3):440–444. https://doi.org/10.1016/j.cognition.2008.12.001

89. Kandel S, Alvarez C, & Vallée, N. Syllables as processing units in handwriting production. J Exp Psychol Hum Percept Perform. 2006;32(1):18–31. https://doi.org/10.1037/0096-1523.32.1.18

90. Baddeley A. The episodic buffer: a new component of working memory? Trends Cogn Sci. 2000;4(11):417–423. https://doi.org/10.1016/S1364-6613(00)01538-2

91. Berninger VW, Abbott RD, Cook CR, Nagy W. Relationships of attention and executive functions to oral language, reading, and writing skills and systems in middle childhood and early adolescence. J Learn Disabilities. 2017;50(4):434–339. https://doi.org/10.1177/0022219415617167

92. Cowen N. What are the differences between long-term, short-term, and working memory? Prog Brain Res. 2008;169:323–338. https://doi.org/10.1016/S0079-6123(07)00220-9

93. Kellogg RT. A model of working memory in writing. In: C. M. Levy CM, Ransdell S, editors. The science of writing: theories, methods, individual differences, and applications. Lawrence Erlbaum Associates, Inc; 1996. pp. 57–71.

94. McCabe DP, Roediger HL, McDaniel MA, Balota DA, Hambrick DZ. The relationship between working memory capacity and executive functioning: evidence for a common executive attention construct. Neuropsychology. 2010;24(2):222–243. https://doi.org/10.1037/a0017619
95. Olive T. Working memory in writing. In: Berninger VW, editor. Past, present, and future contributions of cognitive writing research to cognitive psychology. New York (NY): Psychology Press; 2011. pp. 485–506.

96. Olive, T. Writing and working memory: a summary of theories and of findings. In: Grigorenko EL, Mambrino E, Preiss DD, editors. Writing: a mosaic of new perspectives. Psychology Press; 2012. pp. 125–140.

97. Tse LFL, Thanapalan KC, Chan CCH. Visual-perceptual-kinesthetic inputs on influencing writing performances in children with handwriting difficulties. Res Dev Disabilities. 2014;35(2):340–347. https://doi.org/10.1016/j.ridd.2013.11.013

98. Dharani K. The biology of thought: a neuronal mechanism in the generation of thought — a new molecular model. Elsevier Science Publishing Co. Inc.; 2015. p. 57. https://doi.org/10.1016/B978-0-12-800900-0.00007-5

99. Aben B, Stapert S, Blokland A. About the distinction between working memory and short-term memory. Front Psychol. 2012;3(301):1–9. https://doi.org/10.3389/fpsyg.2012.00301

100. Schneck CM. A frame of reference for visual perception. In: Kramer P, Hinojosa J, editors. Pediatric occupational therapy. 3rd ed. Philadelphia: Lippincott, Williams & Wilkins; 2010. pp. 349–389.

101. Olive T. Toward a parallel and cascading model of the writing system: a review of research on writing processes coordination. J Writ Res. 2014;6(2):173–194. https://doi.org/10.17239/jowr-2014.06.02.4

102. Berninger VW, Abbott RD, Jones J, Wolf BJ, Gould L, Anderson-Youngstrom M, et al. Early development of language by hand: composing, reading, listening, and speaking connection; three letter-writing models; and fast mapping in spelling. Dev Neuropsychol. 2006;29(1):61–92. https://doi.org/10.1207/s15326942dn2901_5