Reading and Writing (2024) 37:205–237
https://doi.org/10.1007/s11145-023-10418-2

Spelling processing during handwriting and typing and the role of reading and visual-motor skills when typing is less practiced than handwriting

Tania Cerni[1,3] · **Remo Job**[2,3]

Accepted: 18 January 2023 / Published online: 8 March 2023

Abstract

The automatization of handwriting and typing is sustained by both sensorimotor and linguistic abilities that support the integration of central-linguistic processes with modality-specific peripheral-motor programs. How this integration evolves when handwriting and, especially, typing is not fully automatized has not been well-understood yet. In the present work, we had two main aims: (1) to understand how spelling processing affects handwriting and typing word production in a sample of 9th-grade Italian students who have extensive handwriting practice but less experience with typing, and (2) to unveil if reading and visual-motor integration skills of the writer/typists have a role in integrating spelling processing and motor execution. Thirty-six 9th-grade participants handwrote and typed to dictation words and pseudowords of different lengths and orthographic complexity. To test spelling processing during handwriting and typing, we collected measures of latency (RTs)—i.e. the interval between spoken stimulus availability and starting to write—, of interletter interval mean—i.e., the mean of the intervals between consecutive letters—, and whole response duration—i.e. the execution time of the entire stimulus. We further assessed participants' reading and visual-motor integration skills to analyze their impact on the chronometric measures as a function of the linguistic proprieties of the stimuli. Our findings show a different pattern of processing for handwriting, the automatized process for our participants, and for typing, for which stronger lexical and sublexical effects emerged. Furthermore, reading and visual-motor skills interacted differently with the two transcription modalities unveiling a modality-specific role of individual skills according to the automatization of handwriting and typing.

Keywords Keystrokes · Linguistic processing · Orthography · Sensorimotor processes · Spelling · Transcription · Writing

---

✉ Tania Cerni
tania.cerni@unipd.it; tania.cerni@gmail.com

Extended author information available on the last page of the article

Introduction

Nowadays, with the large diffusion of mass technology, when we talk about "writing", intended as a low-level transcription process, we refer not only to handwriting but also to typing. Broadly speaking, typing has just overcome handwriting in both social and working life as electronic typed texts are widespread. Despite the prominent role of typing, this transcription process has been less considered than handwriting in both research and educational practice, and typing formal instruction is not systematically delivered in compulsory schooling in many countries (Berninger et al., 2015; Poole & Preciado, 2016; Spilling et al., 2022; Hayley Weigelt-Marom & Weintraub, 2018). For instance, Italian schools—where the present research was conducted—provide children with handwriting instruction during literacy acquisition, but do not have explicit didactic plans for typing (MIUR, 2012, 2018). As a consequence, typing proficiency is often self-constructed through practice (Grabowski, 2008; Pinet et al., 2022), in spite of the fact that training fluency in typing proved to be effective in improving spelling as well as composition at different ages (van Weerdenburg et al., 2019; Weigelt-Marom & Weintraub, 2015; Yechiam et al., 2003). Actually, fluent transcription processes are fundamental in written production, whether it is typing or handwriting. Their automatization enables cognitive resources to be invested less in low-level sensorimotor processes and more in higher-level writing processes (for meta-analytic review, see e.g., Feng et al., 2019; Kent & Wanzek, 2016). Therefore, reaching this automatization is a primary goal in writing acquisition.

From a pure sensorimotor perspective, the evolution from discontinuous to fluent handwriting gestures seems to be driven by the automatization in integrating visual and proprioceptive information (for a review, see Palmis et al., 2017). During handwriting acquisition, children start paying attention to the movements they perform while monitoring the product of writing (the trace). Around 9–10 years, their handwriting is quite automatic with no need for effortful control of motor processes, and fluency grows more slowly than in previous years, reaching adult standards around the 9th grade (Graham et al., 2010). For typing, the attention of a non-expert typist oscillates between the key location, the unfixed position of hands, and the screen in order to monitor both the process and the product of typing (Connelly et al., 2007; Johansson et al., 2010; van Weerdenburg et al., 2019; Yechiam et al., 2003). When a typing strategy is automatized, be it the formal touch-typing method or a personal strategy, the typist relies on kinesthetic more than visual feedback and the cognitive effort is less devoted to motor control and more to content (Grabowski & Mathiebe, 2018).

Importantly, these sensorimotor aspects are not the only building blocks of writing, but they have to be integrated with linguistic processes (e.g., Afonso et al., 2020a). In other words, writing is not only a matter of producing letter shapes or tapping keys, but it also includes spelling processes linked to lexical and sublexical features (Berninger, 1999). Transcription fluency is thus dependent on both sensorimotor and linguistic aspects. In the present work, we aimed to study how young students with different levels of handwriting and typing automatization deal with spelling during word production in a writing-to-dictation task, and how individual linguistic and sensorimotor skills contribute to integrating spelling in the two transcription modalities.

The interacting nature of transcription processes: differences between handwriting and typing

Psychological and neuropsychological models of written word production distinguish spelling processes, which refer to central-linguistic aspects of writing, and handwriting- and typing-specific processes, which refer to peripheral-motor aspect of writing (Magrassi et al., 2010; Planton et al., 2013; Purcell et al., 2011b; Tainturier & Rapp, 2001; Van Galen, 1991). Central processes operate on self-generated or external verbal stimuli and are responsible for converting them into orthographic representations—through the lexical or the sublexical path according to dual-route models (Barry, 1994; Perry & Ziegler, 2018; Rapp et al., 2002)—and for maintaining them in working memory (i.e., in the graphemic buffer, Caramazza et al., 1987). Peripheral processes convert these representations into motor commands. Therefore, they involve specific sensorimotor processes depending on the tool used to produce the written output, e.g., the pen or the keyboard. Handwriting and typing differ in the mechanisms involved in retrieving, programming, and producing letters and corresponding motor commands: in handwriting, arms, hands, and fingers are involved in producing specific strokes that compose letters, which are retrieved from previously selected allographs. In typing, the limbs are instructed to reach keys at specific positions on the keyboard. An expert typist plans and executes interiorized movements schemata, while a non-expert plans the movements after monitoring the letters drawn on keys (for further details on sensorimotor differences between handwriting and typing, see e.g. Cerni & Job, 2022; Mangen & Velay, 2010; Spilling et al., 2022).

A growing body of literature examining written word production sustains that central and peripheral processes interact (e.g., Sumner et al., 2014). Several studies showed that linguistic proprieties of the to-be-written words modulate handwriting and typing online execution of that words—not only the planning phase that precedes the execution, measured as latency, i.e., the time elapsed between the stimulus presentation and the first pen/key press. This evidence is consistent with the view that the construction of the orthographic representation—i.e., spelling—is not terminated before written execution starts, and it was found in both transparent and opaque languages, as well as in logographic scripts (e.g., Afonso & Álvarez, 2019; Afonso et al., 2015; Kandel & Spinelli, 2010; Kandel et al., 2013; Pinet et al., 2016; Planton et al., 2019; Rønneberg & Torrance, 2019; Roux et al., 2013; Scaltritti et al., 2016; Suárez-Coalla et al., 2018; Zhang & Feng, 2017). Regarding handwriting, sublexical variables, such as phoneme-to-grapheme consistency, alter the whole word duration (i.e., the time taken for writing the whole stimulus from the first to the last pen press, Delattre et al., 2006; Planton et al., 2019), the letter and/or stroke duration (i.e., the writing duration of a letter including pen traces and pauses or calculating the mean strokes within a letter, Kandel & Spinelli, 2010; Kandel et al., 2013; Roux et al., 2013), and the interletter intervals (i.e., the time intervals between the end of a letter and the initiation of the following one, Afonso et al., 2015; Kandel et al., 2013). Similar findings emerged for the length (e.g., considering the number of syllables, Álvarez et al., 2009; Kandel & Valdois, 2006a, 2006b; Lambert et al., 2008), as well as for lexical factors such as word frequency and lexicality of the to-be-written stimulus (Delattre et al., 2006; Roux et al., 2013; but see also Afonso et al., 2018). Overall, these results invite the conclusion that spelling processes activation percolates, or "cascades", into handwriting sensorimotor processes.

Regarding typing, studies are less numerous and sometimes inconsistent, with some evidence (Baus et al., 2013; Crump & Logan, 2010; Damian & Freeman, 2008; Logan & Crump, 2009; Logan & Zbrodoff, 1998) showing linguistic effects on typing latency but not on typing execution, and other evidence (Bloemsaat et al., 2003; Gentner et al., 1988; Pinet et al., 2016; Rønneberg & Torrance, 2019; Sahel et al., 2008; Scaltritti et al., 2016; Weingarten et al., 2004) showing that numerous linguistic variables, such as orthographic consistency, orthographic neighborhood size, semantic transparency but also length, syllable structure, and bigram frequency affect IKIs (i.e., the time distance between two consecutive key presses).

In a recent study on adults, Cerni and Job (2022) compared the extent to which spelling processing affects handwriting and typing word dictation with the assumption that the two different motor programs allow for different online processing of the same linguistic variables. The results showed that the linguistic properties of the stimuli affect differently not only latency in starting to handwrite and type, but also the mean duration of InterLetter Intervals (ILIs, the time elapsed between two consecutive letters) and Whole Response Duration (WRD, the time taken to write or type a stimulus from the first to the last pen/key press) in the two production modalities. Findings suggest that the processing of linguistic information, such as lexicality and orthographic complexity, occurs progressively during handwriting gestures (affecting ILIs and/or WRD), while in typing it is anticipated before movement initiation or during the selection of initial letters, and it depends on the length of the stimulus. The authors concluded that the differences between typing and handwriting in gesture planning and execution probably affect the maintenance of the orthographic representation in memory, and, as a consequence, how linguistic processing proceeds during word transcription. While handwriting, being slower and more laborious, requires processing small segments one at a time, typing, being faster and easier, allows processing longer letter sequences in advance. Only when these sequences are long, the spelling processing has to be reloaded.

Spelling processing during handwriting and typing automatization

In general, children at school learn concomitantly handwriting, spelling, and reading (James & Gauthier, 2006; Mangen & Velay, 2010). On the contrary, typing—when it is not formally instructed—is acquired later integrating previously interiorized linguistic skills. Linguistic processes seem to be progressively integrated into handwriting and typing depending on the grade of expertise with the motor programs. For instance, Kandel and Perret (2015) found that the orthographic irregularity and the lexical frequency of a word impact handwriting fluency (number of absolute velocity peaks produced in each letter) already at age 8, progressively becoming more adult-like at age 9 and 10. More specifically, 8- and 9- year-old French children processed orthographic irregularity before starting to write (as showed by slower latency for irregular than for regular words), and this processing percolated during the execution of words, slowing down the duration of the final letters. In 10-year-old children, the orthographic irregularity slowed down the duration of the first and last letters of the words, but the processing did not impact latency. This pattern suggests that older children, with more automated handwriting skills, process linguistic information progressively during writing, similarly to adults (Delattre et al., 2006; Roux et al., 2013). In sum, spelling processing is integrated along with the development of handwriting graphomotor abilities, and during literacy acquisition. This integration seems to start when school children are around 8 years old in both regular and irregular orthographies with a consistent impact of spelling on writing (Afonso et al., 2018; Afonso et al., 2020b; Kandel & Valdois, 2005, 2006a; Kandel et al., 2009, 2011). During handwriting automatization, pure graphomotor skills become more fluent and less cognitively demanding. As a consequence, linguistic processing change, and somehow lighten, its impact on latency and/or fluency (Afonso et al., 2018; Afonso et al., 2020a; Suárez-Coalla et al., 2018).

Considering typing, some of the models of expert touch-typing production suggest that linguistic processing is separate from motor execution (Crump & Logan, 2010; Logan & Crump, 2011). According to this view, an expert should type without the interference of linguistic information. Nevertheless, as we mentioned in the previous section, linguistic information affects typing in different tasks (Pinet et al., 2016; Scaltritti et al., 2016), in users with different levels of expertise (Pinet et al., 2022) and in children (Rønneberg & Torrance, 2019). However, the influence of spelling on unskilled typing has not been extensively investigated and the evidence is not univocal. A few studies comparing different levels of expertise found that high bigram frequency facilitated typing execution—accelerating IKIs—more in expert typists than in novice typists (Behmer & Crump, 2016; Cerni et al., 2016a; Gentner et al., 1988; Grudin & Larochelle, 1982; Ostry, 1983; Salthouse, 1986) but the opposite pattern has also been reported (with bigram frequency affecting low-proficient more than high-proficient typists (Pinet et al., 2022). Thus, how spelling processing integrates with not fully automatized typing skills is not well understood: untargeted studies, few investigated variables, and discordant results leave open the question of whether this processing percolates differently for expert or non-expert typists during writing.

Linguistic and sensorimotor predictors of spelling performed through handwriting and typing

Extensive practice and instructions are not the only factors that play a role in the integration of central and peripheral processes: neurodevelopmental cognitive skills are relevant as well. In particular, linguistic and sensorimotor skills showed to predict transcription (Berninger, 1999). This is true for both handwriting and typing even if studies that looked for common predictors are very scarce and are not targeted to understand the role of these predictors on the integration of linguistic and motor processes.

Among linguistic skills, orthographic coding skills affect handwriting along with its development (Berninger, 1999; Berninger et al., 1992, 1994, 1996), and phonological coding skills predict spelling abilities (Abbott & Berninger, 1993; Burt & Fury, 2000; Stanovich & West, 1989; Ziegler et al., 2000). In general, reading skills and writing skills are related and predictive of one another (e.g., Graham & Hebert, 2011; Graham et al., 2018). On the one hand, transcription processes affect reading development: writing practice facilitates memorization and/or recognition of characters and words for both handwriting (Bara & Gentaz, 2011; Bosse et al., 2014; Longcamp et al., 2003, 2005; Mangen et al., 2015), and typing (Beilock & Holt, 2007; Cerni et al., 2016b; Van den Bergh et al., 1990). On the other hand, the repeated exposition to orthographic word forms through reading boosts spelling proficiency (Burt & Fury, 2000; Ehri, 1997). Word and nonword reading proficiency are positively correlated with spelling accuracy in shallow and deep orthographies as well as in non-alphabetic languages, showing lexical and sublexical effects on spelling in children's handwriting and typing (Babayiĝit & Stainthorp, 2011; Caravolas et al., 2001; Johnston et al., 2014; Rønneberg & Torrance, 2019; Yeung et al., 2013). Notably, studies that tested common handwriting and typing linguistic predictors and their relationship with reading skills are very rare. Berninger et al. (2006) found that speed and accuracy in the two transcription modalities were both related to rapid automatized naming, phoneme analysis, and orthographic coding, although they contributed to speed and/or accuracy at different degrees. However, the two transcription modalities were not directly compared.

Looking at sensorimotor aspects of transcription processes, perceptual and fine motor skills predict handwriting and typing. For instance, during childhood, visual-motor integration—the ability to coordinate visual perception and hand/finger movements (Beery & Beery, 2004)—is positively related to handwriting fluency and legibility (Cornhill & Case-Smith, 1996; Kaiser et al., 2009; Volman et al., 2006; Weintraub & Graham, 2000). In addition, manual dexterity and bimanual coordination are important predictors of spelling, performed through handwriting. Doyen et al. (2017) found that the dominant hand performance in a peg-moving task measured in kindergarten was linked to word spelling accuracy in Grade 1. Interestingly, the non-dominant hand performance was a better predictor of both word and pseudoword spelling accuracy. Recently, Lê et al. (2021) provided evidence that the relationship between manual dexterity and spelling (but also reading) in Grade 3 is mediated by handwriting fluency. Regarding typing, empirical studies are less numerous but confirm the predictive value of visual-motor skills on typing performance. For instance, dexterity measures, such as finger and pencil tapping, positively correlated with typing tests in 3rd- and 4th-grade children (McClurg & Kercher, 1989). Interestingly, few available studies comparing handwriting and typing suggest that the predictors do not fully overlap for the two writing modalities. Preminger et al. (2004) found that visual-motor integration and spatial perception correlated with handwriting accuracy in children, while bilateral coordination correlated with typing accuracy. Speed in both transcription modalities was predicted by tactile perception, but kinesthetic information (e.g., finger opposition) correlated only with typing. In adults, finger function and manual dexterity correlated with handwriting legibility and speed, while fine motor skills predicted the performance of slower (but not faster) typists (Weintraub et al., 2010). This latter result could be interpreted according to a developmental perspective suggesting that fine motor skills decrease their impact on written production when fluency of gestures is reached (Abbott & Berninger, 1993; Berninger, 1999).

The present study

Overall, previous literature relating to the coexistence of linguistic and sensorimotor processes in handwriting and typing suggests that linguistic processing impacts differently the two transcription modalities (Cerni & Job, 2022) and that this impact depends in part on the level of automatization of writing gestures (e.g., Afonso et al., 2020a; Cerni et al., 2016a; Kandel & Perret, 2015). Furthermore, individual skills in the linguistic and sensorimotor domains support written production fluency but it is not clear if their predicting value is the same for handwriting and typing (Berninger et al., 2006; Preminger et al., 2004; Weintraub et al., 2010).

In the present study, we aimed to answer two main research questions: (1) how does spelling processing (central processes) modulate handwriting and typing execution (peripheral processes) in a sample of young adolescents? and (2) how does this modulation depend on the linguistic and sensorimotor skills of the writer/typist?

Regarding the first research question, our sample was a group of Italian 9th-grade students, who were used to handwriting at school and who learned handwriting as a unique transcription skill in primary grades. On the contrary, they started to acquire typing later and autonomously. This educational setting in which handwriting was trained from infancy and typing was later self-acquired is common in many countries (Berninger et al., 2015; Grabowski, 2008; Pinet et al., 2022; Poole & Preciado, 2016; Spilling et al., 2022; Weigelt-Marom & Weintraub, 2018) and allows us to compare a formally trained and automatized transcription modality (i.e. handwriting) with a self-trained, and less automatized one (i.e., typing).

To unveil how linguistic processes percolate in motor processes, we used the same methodological paradigm as Cerni and Job (2022). In detail, participants handwrote and typed to dictation a set of stimuli varying for lexicality (words and pseudowords), length (short and long), and of sound-to-spelling mapping complexity (simple and complex). We measured latency (RTs), assumed to index initial linguistic and motor planning up to the start of movement execution, the mean length of InterLetter Intervals (ILIs), assumed to index local planning of the linguistic units during execution, and Whole Response Duration (WRD), which embraces cumulative effects of planning and execution. If spelling processing affects handwriting and typing, we expected that the linguistic proprieties of the stimuli modulated not only latency but also ILIs and WRDs, showing an influence of linguistic processing during execution. Following Cerni and Job's (2022) results, we expected: (a) slower RTs for pseudowords than for words, with a stronger effect in typing than in handwriting; (b) slower ILIs and WRD for long than for short stimuli, with a stronger effect during typing than during handwriting; (c) slower ILIs for complex than for simple stimuli, with a stronger effect in handwriting than in typing. Crucially, our sample had less automatized typing skills than the adults tested in Cerni and Job (2022),—as we confirmed with a comparative analysis, see Supplementary Table S1 and its explanation in "Participants" and "Results" sections—and, therefore, we expected possible differences with our results. In particular, we hypothesized that lexicality and orthographic complexity would affect typing execution (ILIs and/or WRD) more strongly in the present sample than in adults (for whom the impact of these variables emerged only in interactions with length or in portions of the stimuli). A similar finding would suggest that spelling processing affects more strongly typing when it is less automatized.

As for the second research question, we explored how two individual variables influenced typing and handwriting performance. The first one was reading skills, taken as an index of linguistic abilities since they correlate with various basic linguistic abilities and with spelling (e.g., Abbott & Berninger, 1993; Berninger, 1999; Burt & Fury, 2000; Rønneberg & Torrance, 2019; Yeung et al., 2013), measured by compiling word and pseudoword speed and accuracy reading indices. The second variable was an index of visual-motor integration with the right and the left hands considered as indicators of combined manual dexterity and eye and coordination skills (Beery & Beery, 2004). We assumed that individual indices would interact differently with typing and handwriting chronometric measures, given the differences in linguistic and sensorimotor processing as well as in the level of automatization between the two transcription skills. Therefore, we tested if these indices interacted with writing modalities and linguistic proprieties of the written stimuli, modulating writing execution.

It has to be pointed out that there is no exhaustive research on linguistic processing according to different automatization levels of handwriting and typing. Furthermore, the comparison of how individual skills impact the chronometric measures collected during handwriting and typing is a relevant novelty. Indeed, previous studies did not compare the two modalities, testing only one modality (e.g., Rønneberg & Torrance, 2019), or they analyzed accuracy, legibility, and general speed but not the dynamic of written production (Preminger et al., 2004; Weintraub et al., 2010).

Materials and methods

Participants

Thirty-six 9th-grade Italian students volunteered in the study (22 female, *M* age = 14.75, SD = 0.65). They attended the first year of a local high school. We performed a sensitivity analysis using PANGEA—Power ANalysis for GEneral Anova designs (Westfall, 2016) to justify the sample size. We tested a repeated measure design with two random variables (participants and stimuli) and four independent factors (typing/handwriting and three linguistic variables). Results showed that considering a medium effect size (d = .40), a 3-way interaction would reach a power of .99.

All participants spoke Italian as their first language. Five participants were bilingual, their native language being Portuguese (N = 1), Tunisian Arabic (N = 1), and Albanian (N = 3) but they had lived in Italy since infancy attending only Italian schools during their education. None of the participants reported visual, motor, or hearing impairments, nor cognitive or learning disorders.

All participants, except one, handwrote with their right hand and reported a laterality index from 0.40 to 1.00, measured through the Edinburgh Handedness Inventory (Oldfield, 1971). The left-handed participant reported a laterality index of − 0.70 (total sample mean = 0.87, SD = 0.19). All the participants, except three, typed with two hands, with one to three fingers per hand. Overall, they reported using computers for a mean of 6.39 years (SD = 2.06). As common in Italian schools, they received formal instruction for handwriting since infancy, but not for typing. Handwriting was the primary writing modality used in class at the moment of the study. Keyboards were used only for computer classes (2 h a week) or other sporadic lessons (e.g., foreign language tests).

A self-reported questionnaire was administered to collect information on the average time, in minutes, spent daily reading and writing with pen and paper, on the computer, and on the mobile phone. Details on participants are reported at https://osf.io/aybwf/. Supplementary Materials, Table S1, presents descriptive statistics of the collected information. Overall, participants spent more time reading on papers than on computer screens (paired t-test: $t = 9.05$, $p < .001$). If the reading time on mobile screens was added to the reading time on computers, the difference in comparison to the reading time on paper remained significant ($t = 3.59$, $p = .001$). Regarding writing habits, participants reported spending more time in handwriting than in typing ($t = 7.06$, $p < .001$). If mobile typing minutes were added to the computer typing minutes, the difference between typing and handwriting time remained significant ($t = 2.42$, $p = .021$).

To test whether participants were less used to typing than to handwriting, and, importantly, whether they were less used to typing than adults, we compared their reading and writing habits to those of the adults (mean age = 23.58, SD = 2.91) tested in Cerni and Job (2022) who did not report statistical differences between computer and pen & paper habits. Results (see Supplementary Materials, Table S1) suggested that the present sample read and typed significantly less with the computer than adults, but read and handwrote more with pen and paper.

All the participants took part in the experiment with parental written consent. The study was approved by the ethical committee of the University of Trento [protocol: 2019-008].

Tasks and procedure

All students participated to an individual session in a quiet classroom in the presence of the experimenter. They performed four tasks: a standardized reading assessment, a visual-motor integration task, a typing-to-dictation task, and a handwriting-to-dictation task.

The order of the first two tasks was the same for all the participants, whereas the two dictation tasks were counterbalanced alternating participants who started with the pen or with the keyboard.

Typing- and handwriting-to-dictation tasks

We used the same tasks and stimuli as Cerni and Job (2022) and we referred to this previous work for a complete description of the tasks and the stimuli. To summarize, a list of 56 words and a list of 56 pseudowords were presented separately in each condition (typing and handwriting), alternating the lists between participants. In each list, half of the stimuli were *short* (5–6 letters) and half were *long* (8–9 letters); within each length set, half of the stimuli were orthographically *simple*, with a 1:1 phoneme-to-grapheme correspondence, and half orthographically *complex*, with a variety of Italian orthographic complexities ([k] – *ch*, [g] – *gh*, [ʃ] – *sc*, [ʎ] – *gli*, [ɲ] – *gn*; orthographic ambiguities: [tʃe] – *ce*/*cie*, [ʃe] – *sce*/*scie* and [kw] – *cu*/*qu*). Pseudowords were created changing 1–2 letters from short words and 2–3 letters from long words. Complex pseudowords maintained the same complexity in the same position as the corresponding words.

The lists were controlled for several linguistic and task-related variables within and between each list. Differences between simple and complex stimuli persisted for bigram frequency, strokes per letter mean, and letter frequency, as well as a difference between long and short stimuli considering orthographic neighborhood size. The complete lists of stimuli with the controlled variables are available at: https://osf.io/aybwf/.

To type and handwrite, participants used a tablet (see "Equipment" section). For the typing task, participants heard a stimulus on each trial and typed it on a physical keyboard. The typed letters appeared at the center of the tablet screen one at a time, as in common word processors. In the handwriting task, participants handwrote the stimulus on the tablet surface on a line at the center of the screen. They wrote in uppercase letters as this encourages lifting the pen naturally between letters, and allowed us to detect interletter intervals for data analysis. Participants self-regulated the duration of the trials, pressing the Return key to hear the next stimulus in the typing condition, or pressing the pen on a virtual red arrow at the right of the line in the handwriting condition. No time limits were set, but participants were encouraged to write/type fast and accurately. In both tasks, four practice trials ensured that participants understood the procedure and familiarized themselves with the equipment.

Reading assessment

To obtain a measure of reading proficiency, we administered the Word Reading and the Nonword Reading subtests from *Batteria per la Valutazione della Dislessia e della Disortografia Evolutiva-2* (Developmental Dyslexia and Dysgraphia Battery-2, Sartori et al., 2007). These subtests require reading aloud as fast and accurately as possible a list of 112 Italian words and a list of 48 pseudowords with increasing complexity and length. Reading time in seconds and accuracy scores for each list were collected.

Visual-motor integration task

This task took inspiration from Bramão et al. (2007). It aimed at measuring the visual scanning processes and manual dexterity with the right and the left hand by requiring participants to click on squares appearing abruptly in different positions on a screen. During this task, a grid of 64 per 36 grey squares of 32 × 32 pixels each stayed fixed on a tablet screen, laid in a horizontal position. The grid was ideally divided into 4 quadrants of 18 per 32 squares each: top-right, top-left, bottom-right, and bottom-left. Each trial started when the participant clicked with a special pen (see "Equipment" section) on a white square of 64 × 64 pixels at the center of the grid. This central square changed its color to a light grey to signal the click was successful. Participants were instructed to keep the pen on the central square until one of the squares of the grid turned black. That being the target, participants had to touch it with the pen and then return to the central point. On each trial, the target appeared on the grid at different time intervals: immediately (0 ms), after 2500 ms, or after 5000 ms. It stayed on until a response was given or for a maximum of 2000 ms. Figure 1 schematizes the trial. The target appeared 12 times in a random position on each quadrant (48 total trails), 4 times in each of the time intervals.

The instruction stressed both accuracy and velocity and the need to bring the pen back to the central point. Participants were encouraged to grasp the pen from the top—with a thumb-2 or -3 fingers grasp—not mimicking the writing grasp, to avoid covering the screen with the arm, and to avoid similarities with writing gestures (see Fig. 1 for a drawing representation). The grasp of the pen, the small dimension of the target, and the unpredictable time intervals ensured an acceptable difficulty of the task. The task was performed twice: one time with the right hand and one

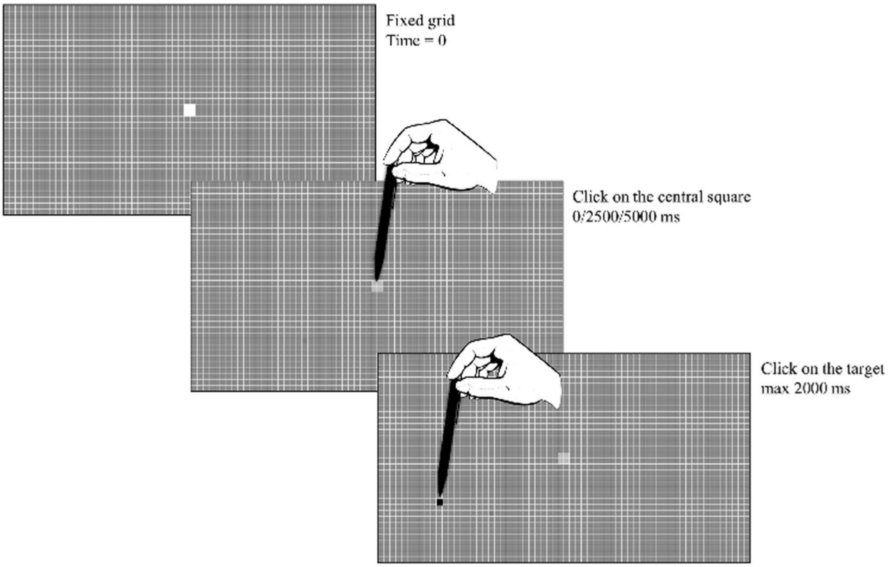

Fig. 1 Trial scheme of the Visual-motor integration task

time with the left hand, alternating the initial hand between participants. Before the beginning of the task, participants performed 12 practice trials. We collected reaction time in ms—i.e., the time elapsed between the moment the target appeared and the moment it was clicked,—and error rates—i.e., the clicking of any square other than the target, or missing responses.

Equipment

Data were collected with a tablet PC Samsung Galaxy Book 12″ (refresh rate: 60 Hz) running a 64-bit version of Windows 10 Pro 1903. During the typing task, it was set in desktop modality, with a customized physical keyboard. During the handwriting task and the visual-motor integration task, the tablet PC was set in tablet modality, lying the device horizontally on a desk. For these latter tasks, we used the S-Pen, a specific pen integrated with the tablet PC and ergonomically equal to a normal pen. It has a 0.7 mm tip and can differentiate 4096 levels of pressure (tested mean sampling frequency: 240 Hz).

Stimulus presentation and response recordings were controlled through the software OpenSesame 3.2.7 (Mathôt et al., 2012) in the typing and visual-motor integration tasks, and through the software Eye and Pen 3.0.0-13 (Alamargot et al., 2006) in the handwriting tasks. The acoustic stimuli for the typing and handwriting tasks were recorded by a male Italian native speaker and edited with Audacity 2.3.3 (Audacity Team, 2019). Participants heard the stimuli through headphones.

Data preparation and statistical analysis

Data preparation

We collected three writing chronometric measures: (1) Reaction Times (RTs), (2) Inter Letter Interval means (ILIs), and (3) Whole Response Duration (WRD). RTs (also referred to as response latency) corresponded to the time taken for the first pen press on the screen, or for the first keypress, from the onset of the stimulus. ILIs were calculated as the mean of all the time intervals between two consecutive letters in a stimulus. Thus an ILI corresponds to the time elapsed between two consecutive keypresses (usually called interkey/interkeystroke interval in typing literature, e.g., Crump & Logan, 2010; Logan & Crump, 2011; Waes et al., 2021) or a pen lift between two consecutive letters (pen pressure = 0, e.g., Kandel et al., 2006). ILIs were manually extracted from the recorded pen lifts, eliminating lifts within letters. An independent rater controlled almost 29% of the data, equally distributed between participants, words, and pseudowords. The inter-rater reliability (Cohens' kappa) was .94. Lastly, WRD was the total time taken to type/handwrite the entire stimulus, from the first to the last pen press or keypress. Note that WRD does not include RTs.

Before the analysis, we removed 12.15% of the trials in the handwriting task and 15.43% in the typing task. These data points corresponded to misspelled stimuli and stimuli with corrections that prevent calculating ILIs and WRD (stimuli that contained a backspace press in typing and stimuli with pen corrections in handwriting).

Outliers were identified and removed for each chronometric measure (3.28% of trials for RTs, 2.37% for ILIs, and 1.09% for WRD) thanks to the recursive procedure with moving criterion (Van Selst & Jolicoeur, 1994). Final datasets are available at: https://osf.io/aybwf/.

Four Inverse Efficiency Scores (IESs) were calculated for each participant as reading proficiency and visual-motor integration indices. IES is a global metric of performance that combines speed and accuracy (Statsenko et al., 2020; Townsend & Ashby, 1978; Vandierendonck, 2017). For the reading assessment, we considered two IES: Words reading IES and Non-words reading IES, calculated as the total number of seconds taken for reading each list, divided by 1 minus the percentage of errors. For the visual-motor integration task, we calculated the Dominant hand IES and the Non-Dominant hand IES. These indices were calculated as the correct reaction times (in ms) with the dominant or the non-dominant hand divided by 1 minus the respective percentage of errors. The higher the IES the worst (slower) the performance in both reading and visual-motor integration tasks.

Statistical analysis

Statistical analysis was performed in R (version 4.1.2; R Core Team, 2021) with linear mixed-effect models (lmerTest package, version 3.1-3; Kuznetsova et al., 2017). RTs, ILIs and WRD were the dependent variables of three separate models. They were log-transformed to approach normal distribution and to meet model assumptions. Continuous predictors were standardized.

Model construction proceeded through a 4-block stepwise procedure that alternates forward and backward selection (for a similar procedure, see Scaltritti et al., 2019). In each block, variables of interest were incrementally added as fixed effects in two model steps, which were compared through a chi-square likelihood ratio test. Before proceeding to the next block, the resulting model was simplified refitting it without predictors that did not reach significance (backward selection following the marginality principle). This model was then tested through a likelihood ratio test against the model with all the predictors, as well as against the final model of the preceding block.

In the first block (block 0), we started with a zero model, with by-participant and by-stimuli random intercepts and slopes (step 0.0). Then, we added linguistic and task-dependent predictors that were not balanced between stimuli categories (bigram frequency, orthographic neighborhood size, strokes per letter mean, and mean letter frequency) and trial order (step 0.1). Block 1 was devoted to testing our first research question on the impact of spelling processing during handwriting and typing considering the three linguistic variables. In this block, we added the manipulated experimental factors (step 1.0): Task (handwriting vs typing), Lexicality (words vs pseudowords), Orthographic Complexity (simple vs complex), and Length (short vs long). In step 1.1, we tested three interactions: Task × Lexicality, Task × Orthographic Complexity, and Task × Length. Individual skills were incrementally added in blocks 2 and 3 to assess the second research question on the possible effect of these skills on writing/typing chronometric measures depending not only on the task modality but also on the interaction between task modality and linguistic variables.

Thus, in block 2 we added reading indices: Word Reading IES and Nonword Reading IES (step 2.0) and their interactions with the terms retained in the previous block (step 2.1). Lastly, in the last block (block 3), we added visual-motor indices: Dominant hand IES and Non-Dominant hand IES, following the same procedure as block 2. Supplementary Materials (Table S2) reports the details of blocks and steps. In all the models, we finally allowed by-participant and by-stimuli intercepts. Slopes were not included due to singularity or convergence failure.

In the "Result" section, we reported the results of the final models for RTs, ILIs, and WRD obtained after block 3. In these models, we considered significant t values higher than 1.96 (p values obtained via the Satterthwaite approximation are additionally reported). We computed multiple comparisons for significant interactions calculated through the functions *emmeans* (for categorical predictors) and *emtrends* (for continuous predictors) in *emmeans* package (version 1.7.2; Lenth, 2022). In detail, we reported t values and p values with Šidák corrections, which corresponded to contrasts for categorical predictors, and tests against slope = 0 for continuous predictors. Lastly, interactions of interest were plotted using the *plot_model* function in *sjPlot* package (version 2.8.10, Lüdecke, 2021).

Results

In Supplementary Materials, Table S1, we present the descriptive statistics of the collected measures: Reading proficiency IES, Visual-motor integration IES, and typing and handwriting RTs, ILIs, and WRD. We further report the results of the comparison between the present sample and the adult sample tested in Cerni and Job (2022) on RTs, ILIs, and WRD separately for the two writing modalities. Six independent t-tests showed that handwriting RTs were similar in the two samples; adolescents were slower than adults in all the other measures in both writing modalities. Notably, typing measures show the largest differences between the two samples. Supplementary Materials, Table S2, lists the results of model comparisons (forward stepwise selection) for RTs, ILIs, and WRD. In the following section, we present the final models for each dependent variable.

Reaction times (RTs)

Table 1 reports the parameters of the final model for RTs obtained after the last block of model comparisons. Figure 2 depicts graphically the significant interactions.

Considering the effect of spelling processes on RTs, Task interacted significantly with Lexicality showing different effects of lexical processing before handwriting and typing started (see Fig. 2, panel A). Post hoc comparisons revealed that starting to type a pseudoword was more time-consuming than starting to type a word ($t = 3.68$, $p < .001$), whereas this lexicality effect was not present in handwriting ($t = 1.84$, $p = .130$). In addition, the significant interaction between Length and Task (see Fig. 2, panel B) pointed out that there was a slight but not significant delay in

Table 1 Results of the mixed-model analysis on RTs

Random effects	Variance	SD
Participants	0.010	0.102
Items	0.004	0.060
Residuals	0.043	0.208

Fixed effects	Estimate	Lower CI	Upper CI	*t*	*p*
Intercept	6.599	6.555	6.643	286.889	<.001
Trial order	−0.021	−0.026	−0.016	−8.044	<.001
Bigram frequency mean	−0.019	−0.033	−0.005	−2.607	.010
Orth. neighborhood size	−0.026	−0.050	−0.003	−2.173	.032
Task	0.204	0.187	0.221	23.465	<.001
Lexicality	0.026	−0.001	0.053	1.843	.067
Length	0.023	−0.021	0.067	1.001	.319
Word reading IES	0.041	0.007	0.075	2.359	.024
Dominant hand IES	0.066	0.032	0.100	3.716	.001
Task × lexicality	0.026	0.006	0.046	2.537	.011
Task × length	−0.022	−0.042	−0.002	−2.137	.033
Task × word reading IES	−0.016	−0.026	−0.006	−3.115	.002
Task × dominant hand IES	−0.060	−0.070	−0.050	−11.752	<.001

Reference levels for categorical predictor: Task = Handwriting, Lexicality = Words, Length = Short. Lower and Upper CI represent 95% confidence intervals

RTs Response times, *IES* Inverse efficiency score

starting long stimuli compared to short stimuli in handwriting ($t = 1.00$, $p = .536$) but not in typing ($t = 0.05$, $p = .999$).

Looking at the effect of individual skills, Word Reading IES and Dominant hand IES yielded additive effects to the model. The main effects were qualified by their significant interactions with Task (see Fig. 2, panel C and panel D). Higher word reading proficiency, indexed by smaller Word Reading IES, entailed faster RTs, significantly in handwriting ($t = 2.36$, $p = .024$) but not in typing ($t = 1.45$, $p = .157$). Similarly, better visual-motor skills with the dominant hand, indexed by smaller Dominant hand IES, predicted faster RTs in starting to handwrite ($t = 3.72$, $p = .001$) but not in starting to type ($t = 0.32$, $p = .937$). No interactions between individual indices and linguistic variables emerged, as well as no effects of Orthographic complexity.

Interletter interval mean (ILIs)

Table 2 reports the parameters of the final model for ILIs. Figure 3 depicts graphically the significant interactions.

Task interacted with Lexicality, with Length, and with Orthographic complexity showing that spelling processing had different effect on handwriting and typing.

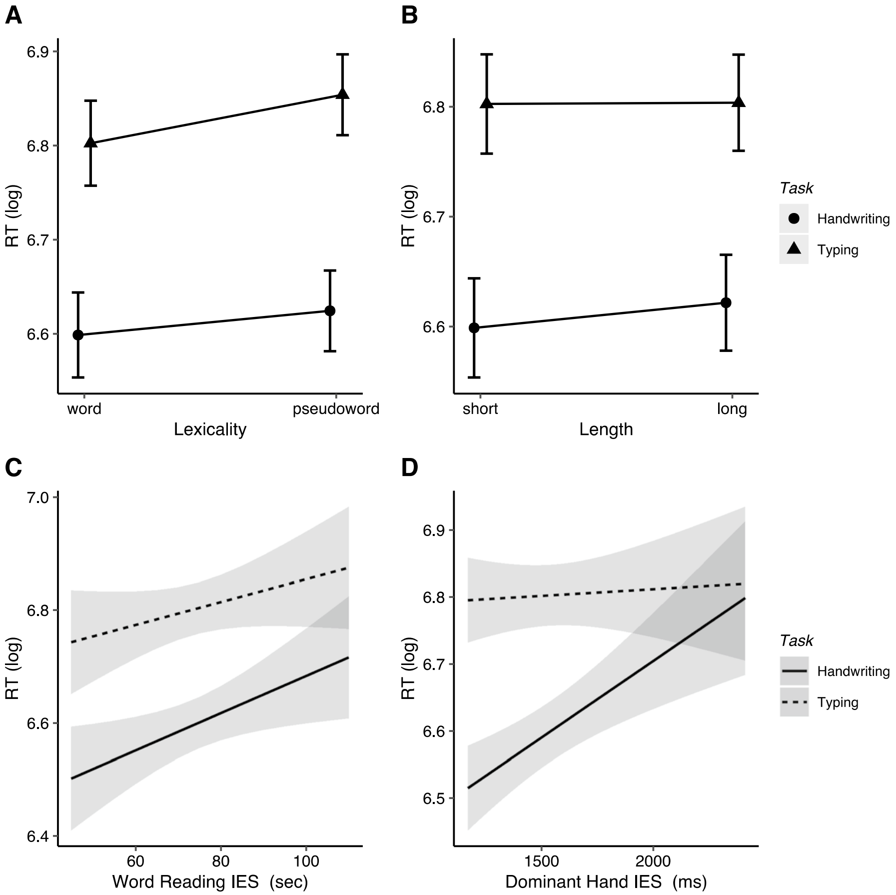

Fig. 2 Graphical representations of significant interactions in the RTs model. *Note* Log-transformed RTs (estimated effects) for the interactions of Task with Lexicality (panel **A**), Length (panel **B**), Word Reading IES (panel **C**), and Dominant Hand IES (panel **D**). Error bars and shaded areas present 95% confidence intervals. *RT* Response time, *IES* Inverse efficiency score

Interletter selection was faster in words than in pseudowords during typing ($t=2.70$, $p=.015$) but not during handwriting ($t=0.27$, $p=.954$, see Fig. 3, panel A). Long stimuli elicited longer ILIs than short ones in typing ($t=5.00$, $p<.001$), whereas the opposite was true in handwriting ($t=-2.65$, $p=.018$, see Fig. 3, panel B). Orthographic complexity affected handwriting ILIs, with slower interletter selection for stimuli with an orthographic complexity ($t=4.36$, $p<.001$), but not typing ILIs ($t=1.27$, $p=.368$, see Fig. 3, panel C).

Reading proficiency was associated differently with handwriting and typing ILIs as shown by the interaction between Task and Word Reading IES (see Fig. 3, panel D) and between Task and Nonword Reading IES (see Fig. 3, panel E). These interactions suggest that (1) better word reading proficiency sustained handwriting, accelerating ILIs ($t=2.54$, $p=.032$), but did not affect typing ($t=-0.13$, $p=.989$)

Table 2 Results of the mixed-model analysis on ILIs

Random effects	Variance	SD
Participants	0.027	0.163
Items	0.001	0.035
Residuals	0.065	0.254

Fixed effects	Estimate	Lower CI	Upper CI	*t*	*p*
Intercept	5.092	5.035	5.148	167.735	<.001
Trial order	−0.022	−0.028	−0.016	−6.995	<.001
Bigram frequency mean	−0.019	−0.029	−0.009	−3.541	.001
Orth. neighborhood size	−0.025	−0.042	−0.008	−2.862	.005
Task	0.439	0.415	0.462	36.090	<.001
Lexicality	0.003	−0.019	0.025	0.273	.785
Length	−0.046	−0.080	−0.012	−2.646	.009
Orthographic complexity	0.049	0.027	0.070	4.362	<.001
Word reading IES	0.079	0.021	0.137	2.540	.016
Nonword reading IES	0.043	−0.014	0.100	1.423	.164
Dominant hand IES	0.015	−0.060	0.090	0.375	.710
Non-dominant hand IES	0.026	−0.050	0.101	0.631	.532
Task × lexicality	0.028	0.003	0.052	2.230	.026
Task × length	0.134	0.109	0.158	10.774	<.001
Task × orthographic complexity	−0.034	−0.058	−0.010	−2.762	.006
Task × word reading IES	−0.083	−0.097	−0.069	−11.884	<.001
Task × nonword reading IES	0.032	0.019	0.046	4.710	<.001
Task × dominant hand IES	0.034	0.016	0.052	3.744	<.001
Task × non-dominant hand IES	−0.028	−0.050	−0.007	−2.547	.011
Length × non-dominant hand IES	0.005	−0.012	0.021	0.535	.593
Task × length × non-dominant hand IES	−0.027	−0.051	−0.003	−2.187	.029

Reference levels for categorical predictor: Task = Handwriting, Lexicality = Words, Orthographic complexity = Simple, Length = Short. Lower and Upper CI represent 95% confidence intervals

ILIs Interletter Interval mean, *IES* Inverse efficiency score

and (2) better nonword reading proficiency sustained typing, accelerating tying ILIs ($t = 2.49$, $p = .036$), but did not affect handwriting ($t = 1.42$, $p = .302$). Also visual-motor integration proficiency was associated differently with handwriting and typing ILIs, as shown by the interaction between Task and Dominant hand IES. Better dominant hand skills (smaller IES) tended to support the interletter selection more in typing ($t = 1.22$, $p = .407$) than in handwriting ($t = 0.38$, $p = .916$, see Fig. 4, panel F). Finally, the Non-Dominant hand IES interacted with Length and Task. In handwriting, better Non-dominant hand skills corresponded to faster interletter selection in both short and long stimuli ($t = 0.63$, $p = .532$ and $t = 0.75$, $p = .462$, respectively). In typing, better Non-dominant hand IES slightly decelerated ILIs in long stimuli ($t = -0.63$, $p = .536$) whereas the slope was near 0 in short stimuli ($t = -0.07$, $p = .944$).

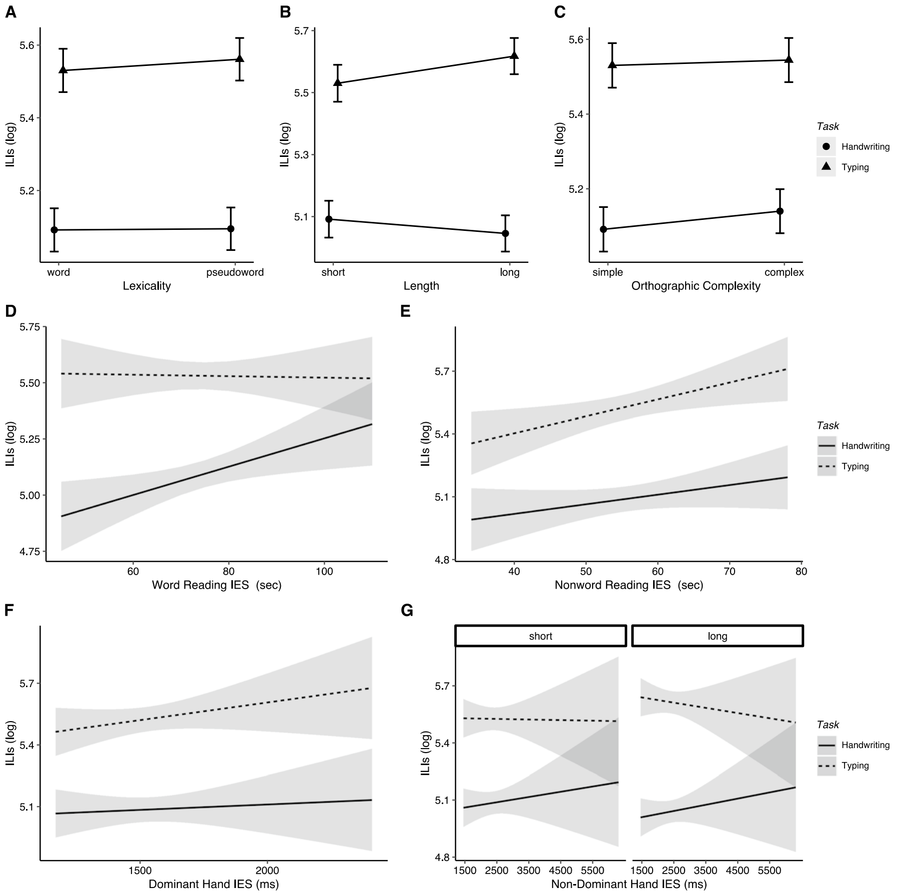

Fig. 3 Graphical representations of significant interactions in the ILI model. *Note* Log-transformed ILIs (estimated effects) for the interactions of Task with Lexicality (panel **A**), Length (panel **B**), Orthographic complexity (panel **C**), Word Reading IES (panel **D**), Nonword Reading IES (panel **E**), Dominant Hand IES (panel **F**), and Non-Dominant Hand IES × Length (panel **G**). Error bars and shaded areas present 95% confidence intervals. *ILI* Interletter interval, *IES* Inverse efficiency score

Whole response duration (WRD)

Table 3 reports the parameters of the final model for WRD. Figure 4 depicts graphically the significant interactions.

For WRD, Task modality interacted with each of the three linguistic variables. The significant interaction between Task and Lexicality (see Fig. 4, panel A) suggests that pseudowords tended to be handwritten ($t = -2.14$, $p = .067$), but not typed ($t = 0.48$, $p = .863$) faster than words. The interaction between Task and Length (see Fig. 4, panel B) shows a stronger length effect (i.e. longer WRD times for longer stimuli) in typing ($t = 21.68$, $p < .001$) than in handwriting ($t = 13.34$, $p < .001$). Finally, the interaction between Task and Orthographic complexity (see Fig. 4, panel

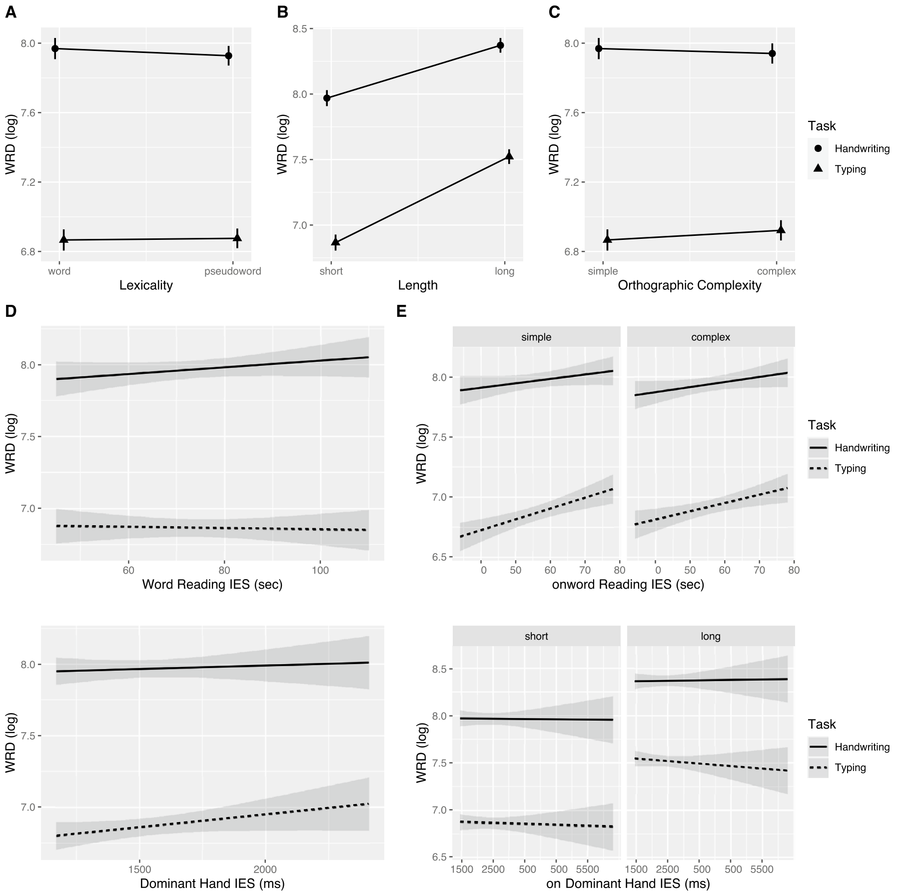

Fig. 4 Graphical representations of significant interactions in the WRD model. *Note* Log-transformed WRD (estimated effects) for the interactions of Task with Lexicality (panel **A**), Length (panel **B**), Orthographic complexity (panel **C**), Word Reading IES (panel **D**), Nonword Reading IES × Orthographic complexity (panel **E**), Dominant Hand IES (panel **F**), and Non-Dominant Hand IES × Length (panel **G**). Error bars and shaded areas present 95% confidence intervals. *WRD* Whole response duration, *IES* Inverse efficiency score

C) shows that stimuli with a complex grapheme were typed more slowly than simple stimuli ($t = 2.78$, $p = .013$) but took about the same time in handwriting ($t = -1.42$, $p = .294$).

Reading proficiency was also associated with a different WRD pattern for the two writing modalities. The interaction between Task and Word Reading IES (see Fig. 4, panel D) points out that better Word Reading IES (smaller values) corresponded to more fluent WRD in handwriting ($t = 1.30$, $p = .365$) but not in typing ($t = -0.24$, $p = .965$). Nonword Reading IES interacted with Task and Orthographic complexity (see Fig. 4, panel E). The better the Nonword Reading IES the faster the typing duration of the stimuli, with the trend being stronger for orthographically

Table 3 Results of the mixed-model analysis on WRD

Random effects	Variance				SD
Participants	0.014				0.118
Items	0.008				0.090
Residuals	0.048				0.218
Fixed effects	**Estimate**	**Lower CI**	**Upper CI**	***t***	***p***
Intercept	7.969	7.910	8.028	256.024	<.001
Trial order	−0.012	−0.017	−0.006	−4.360	<.001
Strokes per letter mean	0.074	0.055	0.093	7.677	<.001
Orth. neighborhood size	−0.142	−0.172	−0.112	−9.192	<.001
Task	−1.103	−1.123	−1.082	−106.740	<.001
Lexicality	−0.041	−0.078	−0.004	−2.142	.034
Length	0.403	0.345	0.461	13.341	<.001
Orthographic complexity	−0.028	−0.067	0.010	−1.415	.160
Word reading IES	0.029	−0.013	0.071	1.300	.203
Nonword reading IES	0.035	−0.007	0.076	1.556	.129
Dominant hand IES	0.014	−0.041	0.069	0.481	.634
Non-dominant hand IES	−0.003	−0.058	0.052	−0.093	.927
Task × lexicality	0.050	0.030	0.071	4.779	<.001
Task × length	0.253	0.232	0.274	23.974	<.001
Task × orthographic complexity	0.084	0.063	0.104	7.938	<.001
Task × word reading IES	−0.035	−0.046	−0.023	−5.834	<.001
Task × nonword reading IES	0.050	0.035	0.066	6.356	<.001
Orthographic complexity × nonword reading IES	0.005	−0.009	0.020	0.707	.480
Task × dominant hand IES	0.038	0.022	0.053	4.826	<.001
Task × non-dominant hand IES	−0.007	−0.025	0.012	−0.734	.463
Length × non-dominant hand IES	0.007	−0.007	0.021	0.970	.332
Task × orthographic complexity × Nonword reading IES	−0.025	−0.046	−0.005	−2.385	.017
Task × length × non-dominant hand IES	−0.022	−0.043	−0.001	−2.081	.037

Reference levels for categorical predictor: Task = Handwriting, Lexicality = Words, Orthographic complexity = Simple, Length = Short. Lower and Upper CI represent 95% confidence intervals

WRD Whole response duration, *IES* Inverse efficiency score

simple stimuli ($t = 3.80$, $p = .001$) than for stimuli with an orthographic complexity ($t = 2.91$, $p = .013$). In handwriting, the same trends were stronger for complex ($t = 1.56$, $p = .242$) than for simple stimuli ($t = 1.79$, $p = .158$), but the slopes were not significantly different from zero. This result shows that the presence of an orthographic complexity did not alter handwriting WRD.

Regarding visual-motor indices, Dominant hand IES interacted with Task (see Fig. 4, panel F): better Dominant hand skills (smaller IES) benefited more typing ($t = 1.77$, $p = .166$) than handwriting WRD ($t = 0.48$, $p = .866$). Non-Dominant hand IES interacted with Task and Length (see Fig. 4, panel G). A better Non-Dominant hand IES slightly increased typing WRD, showing an interference effect, the pattern being emphasized in long ($t = -0.83$, $p = .653$) than in short stimuli ($t = -0.33$, $p = .935$). In handwriting, visual-motor skills with the non-dominant hand did not alter the writing duration of both short ($t = -0.09$, $p = .995$) and long stimuli ($t = 0.15$, $p = .987$).

Discussion

The present study was designed (1) to compare how central-linguistic processes (i.e. spelling) affect typing and handwriting word production in a sample of Italian 9th-grade adolescents, and (2) to test if and how reading and visual-motor skills predict fluency in the two transcription modalities. Regarding the first research question, typing and handwriting were assessed through two dictation tasks in which we collected three chronometric measures: RTs, ILIs, and WRD. Linguistic processing was analyzed by observing how the chronometric measures accelerated or decelerated depending on the linguistic proprieties of the dictated stimuli: lexicality, length, and orthographic complexity. Findings are discussed in "Spelling processes during handwriting and typing" section. Concerning the second question, we assessed participants' word and nonword reading skills, calculating combined indices of speed and accuracy (IES). Similar indices were calculated for visual-motor integration skills of the dominant and non-dominant hands. We analyzed the role of these indices on the chronometric measures as a function of the linguistic proprieties of the stimuli. Findings are discussed in "The role of reading and visual-motor skills" section.

Spelling processes during handwriting and typing

Results confirmed that central processes affect both handwriting and typing execution in 9th-grade adolescents. Spelling processing was not terminated before peripheral processes started as the linguistic variables did affect not only RTs, but also ILIs and WRD, both types of measures sensitive to ongoing processing. Crucially, the spelling impact evolved differently in the two transcription modalities. Considering lexicality, producing a pseudoword in comparison to a word slowed down typing RTs, but also typing execution, especially examining interletter selection (i.e., ILIs). In handwriting, no significant effect of lexicality was found. These results confirmed our expectations, showing that typing requires longer processing of the stimulus before execution, especially for unknown stimuli, i.e. pseudowords. The lexicality processing continues during typing ILIs. It may be worthwhile to compare this pattern with the one obtained with adults (Cerni & Job, 2022). In that study, adult typists showed a deceleration when starting to type a pseudoword, but this deceleration did not percolate on ILIs, except while typing long (but not short) pseudowords—attributed to more demanding working memory processing. In our younger sample, less automatized typing skills prevented exhaustive processing of lexical variables—and anticipated sensorimotor programming—before starting to type. As a consequence, this processing percolated during typing production. This pattern of results is compatible with previous findings sustaining that lexical processing does not affect well-automatized peripheral processes. For instance, lexical frequency affects writing duration only at the beginning of handwriting acquisition but it decreases its impact throughout primary and middle schools (Afonso et al., 2018; Kandel & Perret, 2015). The results are also compatible with the view that central processes decrease or lose their impact on automatized graphomotor skills, especially in transparent orthographies (Suárez-Coalla et al., 2018). This view may also explain the absence of a clear lexicality effect on an automatized process as handwriting (as in Kandel et al., 2006), which could be also hidden by the presence of a stronger effect during the less automatized typing.

Similarly, the length of the stimuli had an expected effect on the two writing modalities. It affected typing more than handwriting execution considering both ILIs and WRD. We attribute this result to the specific processing constraints of typing in maintaining and/or retrieving the orthographic representation (e.g., Caramazza et al., 1987) and do not attribute it to the different experience with the two transcription modalities, as a similar pattern was found also with balanced adult handwriter/typist (Cerni & Job, 2022). Thus, working memory capacity, which commonly influences spelling production, strongly affects typing when the to-be-typed stimuli are long. A second, not incompatible, account refers to the size of the orthographic units used in writing, as the result may also reflect differences in the programming units during typing and handwriting. Syllables are usually identified as possible writing units (Álvarez et al., 2009; Kandel & Valdois, 2006b; Kandel et al., 2006; Lambert et al., 2008; Weingarten et al., 2004). However, previous typing studies found longer interkey intervals located around the third/fifth letter, not necessarily compatible with a single syllable (Larochelle, 1983; Ostry, 1983). On the other hand, handwriting studies showed an interplay between syllables and smaller programming units, such as bigrams, particularly in adults than in less experienced children (Kandel et al., 2011). Thus, it may be that typing relies on orthographic units that may be functional to the task but are not linguistically very familiar and frequent units.

Orthographic complexity affected both typing and handwriting execution but on different chronometric measures: complex stimuli elicited slower ILIs than simple ones in handwriting, while the same effect was observed on WRD in typing. Considering handwriting, results were perfectly in line with data from adults (Cerni & Job, 2022): the presence of a complex grapheme caused a deceleration in letter selection (measured through ILIs), and a slight acceleration of letter production (included in WRD), probably because the complex grapheme was targeted and programmed during the previous ILIs. Considering typing, the effect of the orthographic complexity was more obvious than in adults, for whom the effect was found only by examining portions of the stimuli (Cerni & Job, 2022). As we argued for lexicality, this result suggests a possible impact of the lack of expertise in typing, which increases the effort in programming and keeping in memory the complex linguistic units. Our proposal is that, in slower non-expert typists, cognitive resources are heavily involved in motor programming rather than in spelling, with the consequence that orthographically complex words could not be fully analyzed before starting to type and/or during the previous ILIs. A similar effect of orthographic irregularity on writing duration and fluency measures was observed in younger children learning to handwrite, an effect that decreases throughout primary school (Kandel & Perret, 2015). Overall, these results confirm the hypothesis that spelling processing percolates more significantly on written word production when sensorimotor programming and execution are not fully automatized.

The role of reading and visual-motor skills

Our findings show that reading skills have different effects on typing and handwriting. Word reading IES was positively related to all the chronometric measures in handwriting, while this relationship in typing was weaker or absent. A more efficient lexical access favored a more proficient selection of the to-be-written item—shown by accelerated handwriting RTs,—but also a more proficient online peripheral processing—shown by accelerated handwriting ILIs and WRD. In line with the view that lexical access in reading and spelling share common mechanisms (e.g., Hepner et al., 2017; Jones & Rawson, 2016; Purcell et al., 2017), the pattern we obtained shows that lexical orthographic knowledge in reading is used and exploited during handwriting, the automatized writing mode for our sample. Word reading proficiency, however, did not have a significant impact on typing, suggesting that non-automatized typing relies less on retrieved orthographic representations than on online orthographic analysis of the stimulus string. Interestingly, nonword reading proficiency index predicted more fluent typing than handwriting, as measured by ILIs and WRD, indicating that orthographic decoding skills (without lexical analyses) facilitate typing response execution. Furthermore, better nonword reading skills were more strongly related to faster typing WRD of simple stimuli—that can rely on simple phoneme-to-grapheme conversion rules—than of stimuli with an orthographic complexity, during which sublexical processing has a minor role. This result, together with the strong length effect on typing ILIs and WRD, strengthens the view that typing may require a heavier segmentation processing than handwriting (Cerni & Job, 2022). An additional account for the major role of sublexical reading skills in typing, and the minor role of lexical reading skills, could be the less proficient typing of our participants, which may require finer programming of graphemic units. For example, Rønneberg and Torrance (2019) found that higher scores in a word split task, in which lexical access is crucial, predicted faster ILIs in 6th-grade students who were used to typing at school.

Visual-motor integration skills also had different effects on handwriting and typing. A better dominant hand performance was associated with faster latency in starting handwriting, whereas it had no significant impact on typing. The result is not surprising considering both the fact that handwriting is performed with the dominant hand only and the similarity between handwriting gestures and visual-motor measures. Starting to handwrite requires leaning the pen on a surface with the dominant hand, and the visual-motor integration task measured the rapidity and accuracy of reaching a target with a thin tip. For typing RTs, we expected an effect of both the dominant hand IES and the non-dominant hand IES, given that typing can start with a targeted gesture of one of the two hands. However, the effect did not emerge, indicating that further mechanisms occur during typing, probably more involved in letter identification than in fine movements.

During written execution, better dominant hand skills slightly accelerated ILIs and WRD, more in typing than handwriting. On the contrary, the better the non-dominant hand performance the faster the ILIs and WRD in handwriting. Interestingly, the non-dominant hand had an inhibitory effect in typing, decelerating in particular long stimuli execution. Results on handwriting were in line with previous literature that showed a positive predictive effect of both hands' performance—especially that of the non-dominant hand—on spelling (e.g., Doyen et al., 2017). However, according to previous literature, visual-motor skills lose their prominent role from elementary to intermediate grades along with handwriting automatization (e.g., Berninger, 1999). This major role of visual-motor skills during the automatization of transcription skills could justify the role of dominant hand skills in typing, which appeared greater than in handwriting, being the less automatized production modality.

Within this framework, the opposite direction of the interaction between typing ILIs and WRD with non-dominant hand IES was intriguing. Franceschini et al. (2021) found a similar result regarding pseudoword reading in Italian participants. In detail, pseudoword reading time was negatively related to non-dominant hand performance in the Purdue pegboard task (that measures fingertip and manual dexterity). They interpreted their findings sustaining a possible competition between manual dexterity and pseudoword reading due to the specialization of the dorsal pathway in letter-location coding in proficient readers (the "recycling hypothesis", e.g., Dehaene & Cohen, 2007). The visual dorsal pathway is involved in visual encoding and orthographic processing, but also object location processing (Pammer et al., 2006). It also comprehends the dorsal premotor areas involved in typing (Purcell et al., 2011a, 2011b). In line with this competition mechanism, the ongoing specialization of specific areas in typing programming could compete with the involvement of those areas in fine visual-motor skills. In addition, the relationship we found between typing and pseudoword reading suggests a possible overlap of linguistics and motor mechanisms. An additional explanation is related to the fact that typing is a bimanual action and that a finer specialization of the non-dominant hand could contrast with efficient bimanual alternation, that is essential in skilled typing. Bimanual alternation in typing is governed by activation and inhibition mechanisms. Once a typing sequence that involves both hands is programmed, the contralateral motor cortex is activated, while the ipsilateral motor cortex is inhibited (Pinet et al., 2015). This mechanism is efficient in expert typists whose hand is governed in parallel and whose hand alternation is faster than hand repetition (Cerni et al., 2016a, 2016b; Rumelhart & Norman, 1982), a pattern that is not present in novice typists (Larochelle, 1983). The less proficient typing skills of the present sample can underline not-specialized hand alternation mechanisms. More targeted measures of bimanual skills should be considered in future works to understand the role of manual alternations over and above unimanual skills in typing.

Limitations

We have to address some methodological limitations of the study concerning the complexity of comparing typing and handwriting. First, the use of ILIs as a comparative chronometric measure can be questioned. An ILI corresponds to an interval between two consecutive keypresses in typing and comprehends a letter execution (the first keypress, whereas the second keypress does not include a key release and could not properly be defined as letter execution). In handwriting, an interletter interval corresponds to a pen lift between two consecutive letters, and no letter execution is included. However, ILIs are commonly used in the handwriting and typing literature as a measure of interletter selection, and we interpreted our findings in this vein. A similar point can be raised for RTs, which correspond to the first pen press—without first letter execution—in handwriting and to the first keystroke execution in typing. In this case, we interpreted RTs as a measure to detect linguistic processes before production, assuming that (at least) the first letter selection is planned before starting the writing/typing movement. WRD can help in disentangling the differences between handwriting and typing as it comprises execution and pauses in both modalities. By measuring both WRD and ILIs we believe that we can infer results on both letter selection and letter execution, but we recommend considering these limitations in interpreting the results. Connecting to the choice of comparative measures, our participants handwrote in uppercase letters since it allowed us to extract ILIs. We have to stress that different conclusions on processing dynamics could be found considering e.g., cursive, a more ecological script.

Another methodological limit was the use of different software tools to record typing and handwriting. Handwriting tools are less used and—even if they are well-implemented and updated—they lack all the refinements of more commonly used tools for keypress collection. Moreover, handwriting data segmentation and error detection are manually processed. For this reason, an external rater checked part of the data (inter-rater reliability is reported in "Data preparation and statistical analysis" section).

Finally, our study targeted spelling to dictation and, generally, word production in isolation. Different spelling effects in interaction with writing modality could emerge in sentence and text writing where words are more anchored to their grammatical and lexical contexts. Future studies should be targeted to explore the generalizability of our findings or the specificity of handwriting and typing words in more complex text structures.

Conclusions

To conclude, our findings show that spelling processing percolates differently in handwriting and typing word production in a sample of young adolescents, who have automatized handwriting skills but have no extensive expertise in typing. In comparison to previous results on adults (Cerni & Job, 2022), spelling processing affects handwriting similarly to adults, while lexical and sublexical processing is more pervasive during typing in adolescents than in adults. This result confirms a greater impact of central processes when typing is less automatized, as previously observed for handwriting (Afonso et al., 2018; Kandel & Perret, 2015; Suárez-Coalla et al., 2018). We have provided evidence that spelling processing during written word production depends not only on the writing input modality but also on the level of expertise with that modality. Furthermore, linguistic and sensorimotor skills, such as reading and visual-motor integration indices, have a different impact on the two transcription modalities, showing influences on written execution depending also on the linguistic proprieties of the stimuli. This impact could be due to a modality-specific role of individual skills but also to the automatization stage of handwriting and typing.

Our results suggest that future work in this field should consider that (1) handwriting and typing relate to spelling given the interactive nature of transcription processes, i.e. spelling and writing gestures, and (2) different neurodevelopmental skills affect handwriting and typing, according to the level of expertise with the writing modalities. A direct comparison between groups with different levels of expertise in handwriting and typing can tell us more about how spelling affects motor processes during different steps of handwriting and typing automatization, also according to the individual neurodevelopmental skills. We plan future studies targeted to cross-sectional as well as longitudinal comparisons. Knowing the individual skills that affect typing and handwriting automatization and maintenance is fundamental to sustaining higher-level written language skills (Feng et al., 2019; Kent & Wanzek, 2016; Rønneberg et al., 2022) and language acquisition in general. Students that struggle with transcription skills may be disadvantaged and demotivated in facing writing production. This is true considering handwriting, but also typing which is often untrained and less considered at a sensorimotor level in educational settings.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11145-023-10418-2.

Acknowledgements The authors wish to thank the school head and the teachers for their precious help in organizing the data collection. We thank all the students who participated.

Author contributions Tania Cerni conceived and designed the study. She was responsible for material preparation, data collection, and analysis. She prepared the first draft of the manuscript. Remo Job collaborated in conceiving the study and supervised the work. Both authors revised and approved the final version of the manuscript.

Funding Open access funding provided by Università degli Studi di Padova within the CRUI-CARE Agreement. The present work was financially supported by the Fondazione Cassa di Risparmio di Trento e Rovereto (Caritro), Trento, Italy [Grant Number 2018.0296], and by the Promobilia Foundation, Stockholm, Sweden [Grant Number 19054].

References

Abbott, R. D., & Berninger, V. W. (1993). Structural equation modeling of relationships among developmental skills and writing skills in primary- and intermediate-grade writers. *Journal of Educational Psychology, 85*(3), 478–508. https://doi.org/10.1037/0022-0663.85.3.478

Afonso, O., & Álvarez, C. J. (2019). Measuring writing durations in handwriting research: What do they tell us about the spelling process? In C. Perret & T. Olive (Eds.), *Spelling and writing words* (pp. 151–162). Brill. https://doi.org/10.1163/9789004394988_009

Afonso, O., Álvarez, C. J., & Kandel, S. (2015). Effects of grapheme-to-phoneme probability on writing durations. *Memory and Cognition, 43*, 579–592. https://doi.org/10.3758/s13421-014-0489-8

Afonso, O., Martínez-García, C., Cuetos, F., & Suárez-Coalla, P. (2020a). The development of handwriting speed and its relationship with graphic speed and spelling. *Cognitive Development, 56*, 100965. https://doi.org/10.1016/J.COGDEV.2020.100965

Afonso, O., Suárez-Coalla, P., & Cuetos, F. (2020b). Writing impairments in Spanish children with developmental dyslexia. *Journal of Learning Disabilities, 53*(2), 109–119. https://doi.org/10.1177/0022219419876255

Afonso, O., Suárez-Coalla, P., González-Martín, N., & Cuetos, F. (2018). The impact of word frequency on peripheral processes during handwriting: A matter of age. *Quarterly Journal of Experimental Psychology, 71*(3), 695–703. https://doi.org/10.1080/17470218.2016.1275713

Alamargot, D., Chesnet, D., Dansac, C., & Ros, C. (2006). Eye and Pen: A new device for studying reading during writing. *Behavior Research Methods, 38*(2), 287–299. https://doi.org/10.3758/BF03192780

Álvarez, C. J., Cottrell, D., & Afonso, O. (2009). Writing dictated words and picture names: Syllabic boundaries affect execution in Spanish. *Applied Psycholinguistics, 30*(2), 205–223. https://doi.org/10.1017/S0142716409090092

Audacity Team. (2019). *Audacity(R): Free audio editor and recorder [computer application]. Version 2.3.3*. https://audacityteam.org/

Babayiĝit, S., & Stainthorp, R. (2011). Modeling the relationships between cognitive-linguistic skills and literacy skills: New insights from a transparent orthography. *Journal of Educational Psychology, 103*(1), 169–189. https://doi.org/10.1037/a0021671

Bara, F., & Gentaz, E. (2011). Haptics in teaching handwriting: The role of perceptual and visuo-motor skills. *Human Movement Science, 30*(4), 745–759. https://doi.org/10.1016/j.humov.2010.05.015

Barry, C. (1994). Spelling routes (or roots or rutes). In G. D. A. Brown & N. C. Ellis (Eds.), *Handbook of spelling: Theory, process and intervention* (pp. 27–49). Wiley.

Baus, C., Strijkers, K., & Costa, A. (2013). When does word frequency influence written production? *Frontiers in Psychology, 4*, 963. https://doi.org/10.3389/fpsyg.2013.00963

Beery, K. E., & Beery, N. A. (2004). *Beery VMI: The Beery-Buktenica developmental test of visual-motor integration: Administration, scoring and teaching manual* (5th ed.). NCS Pearson.

Behmer, L. P., Jr., & Crump, M. J. C. (2016). Crunching big data with fingertips: How typists tune their performance toward the statistics of natural language. In M. N. Jones (Ed.), *Big data in cognitive science* (pp. 329–345). Psychology Press. https://doi.org/10.4324/9781315413570-27

Beilock, S. L., & Holt, L. E. (2007). Embodied preference judgments: Can likeability be driven by the motor system? *Psychological Science, 18*(1), 51–57. https://doi.org/10.1111/j.1467-9280.2007.01848.x

Berninger, V. W. (1999). Coordinating transcription and text generation in working memory during composing: Automatic and constructive processes. *Learning Disability Quartely, 22*(2), 99–112. https://doi.org/10.2307/1511269

Berninger, V. W., Abbott, R. D., Jones, J., Wolf, B. J., Gould, L., Anderson-Youngstrom, M., Shimada, S., & Apel, K. (2006). Early development of language by hand: Composing, reading, listening, and speaking connections; three letter-writing modes; and fast mapping in spelling. *Developmental Neuropsychology, 29*(1), 61–92. https://doi.org/10.1207/S15326942DN2901_5

Berninger, V. W., Cartwright, A. C., Yates, C. M., Swanson, H. L., & Abbott, R. D. (1994). Developmental skills related to writing and reading acquisition in the intermediate grades—Shared and unique functional systems. *Reading and Writing, 6*(2), 161–196. https://doi.org/10.1007/BF01026911

Berninger, V. W., Nagy, W., Tanimoto, S., Thompson, R., & Abbott, R. D. (2015). Computer instruction in handwriting, spelling, and composing for students with specific learning disabilities in grades 4–9. *Computers & Education, 81*, 154–168. https://doi.org/10.1016/J.COMPEDU.2014.10.005

Berninger, V. W., Whitaker, D., Feng, Y., Swanson, H. L., & Abbott, R. D. (1996). Assessment of planning, translating, and revising in junior high writers. *Journal of School Psychology, 34*(1), 23–52. https://doi.org/10.1016/0022-4405(95)00024-0

Berninger, V. W., Yates, C., Cartwright, A., Rutberg, J., Remy, E., & Abbott, R. D. (1992). Lower-level developmental skills in beginning writing. *Reading and Writing, 4*(3), 257–280. https://doi.org/10.1007/BF01027151

Bloemsaat, G., Van Galen, G. P., & Meulenbroek, R. G. J. (2003). Lateralized effects of orthographical irregularity and auditory memory load on the kinematics of transcription typewriting. *Psychological Research Psychologische Forschung, 67*(2), 123–133. https://doi.org/10.1007/s00426-002-0112-7

Bosse, M. L., Chaves, N., & Valdois, S. (2014). Lexical orthography acquisition: Is handwriting better than spelling aloud? *Frontiers in Psychology, 5*(Feb), 56. https://doi.org/10.3389/fpsyg.2014.00056

Bramão, I., Mendonça, A., Faísca, L., Ingvar, M., Peterson, K. M., & Reis, A. (2007). The impact of reading and writing skills on a visuo-motor integration task: A comparison between illiterate and literate subjects. *Journal of the International Neuropsychological Society, 13*(2), 359–364. https://doi.org/10.1017/S1355617707070440

Burt, J. S., & Fury, M. B. (2000). Spelling in adults: The role of reading skills and experience. *Reading and Writing: An Interdisciplinary Journal, 13*(1–2), 1–30. https://doi.org/10.1023/A:1008071802996

Caramazza, A., Miceli, G., Villa, G., & Romani, C. (1987). The role of the Graphemic Buffer in spelling: Evidence from a case of acquired dysgraphia. *Cognition, 26*(1), 59–85. https://doi.org/10.1016/0010-0277(87)90014-X

Caravolas, M., Hulme, C., & Snowling, M. J. (2001). The foundations of spelling ability: Evidence from a 3-year longitudinal study. *Journal of Memory and Language, 45*(4), 751–774. https://doi.org/10.1006/jmla.2000.2785

Cerni, T., & Job, R. (2022). The interaction of central and peripheral processes in typing and handwriting: A direct comparison. *Journal of Experimental Psychology: Human Perception and Performance, 48*(6), 563–581. https://doi.org/10.1037/XHP0001006

Cerni, T., Longcamp, M., & Job, R. (2016a). Two thumbs and one index: A comparison of manual coordination in touch-typing and mobile-typing. *Acta Psychologica, 167*, 16–23. https://doi.org/10.1016/j.actpsy.2016.03.007

Cerni, T., Velay, J. L., Alario, F. X., Vaugoyeau, M., & Longcamp, M. (2016b). Motor expertise for typing impacts lexical decision performance. *Trends in Neuroscience and Education, 5*(3), 130–138. https://doi.org/10.1016/j.tine.2016.07.007

Connelly, V., Gee, D., & Walsh, E. (2007). A comparison of keyboarded and handwritten compositions and the relationship with transcription speed. *The British Journal of Educational Psychology, 77*(2), 479–492. https://doi.org/10.1348/000709906X116768

Cornhill, H., & Case-Smith, J. (1996). Factors that relate to good and poor handwriting. *American Journal of Occupational Therapy, 50*(9), 737–739. https://doi.org/10.5014/ajot.50.9.732

Crump, M. J. C., & Logan, G. D. (2010). Hierarchical control and skilled typing: Evidence for word-level control over the execution of individual keystrokes. *Journal of Experimental Psychology: Learning Memory and Cognition, 36*(6), 1369–1380. https://doi.org/10.1037/a0020696

Damian, M. F., & Freeman, N. H. (2008). Flexible and inflexible response components: A Stroop study with typewritten output. *Acta Psychologica, 128*(1), 91–101. https://doi.org/10.1016/j.actpsy.2007.10.002

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron, 56*(2), 384–398. https://doi.org/10.1016/J.NEURON.2007.10.004

Delattre, M., Bonin, P., & Barry, C. (2006). Written spelling to dictation: Sound-to-spelling regularity affects both writing latencies and durations. *Journal of Experimental Psychology: Learning Memory and Cognition, 32*(6), 1330–1340. https://doi.org/10.1037/0278-7393.32.6.1330

Doyen, A. L., Lambert, E., Dumas, F., & Carlier, M. (2017). Manual performance as predictor of literacy acquisition: A study from kindergarten to Grade 1. *Cognitive Development, 43*, 80–90. https://doi.org/10.1016/J.COGDEV.2017.02.011

Ehri, L. (1997). Learning to read and learning to spell are one and the same, almost. In C. A. Perfetti, L. Rieben, & M. Fayol (Eds.), *Learning to spell: Research, theory, and practice across languages* (pp. 237–269). Lawrence Erlbaum Associates Publishers.

Feng, L., Lindner, A., Ji, X. R., & Malatesha Joshi, R. (2019). The roles of handwriting and keyboarding in writing: A meta-analytic review. *Reading and Writing, 32*(1), 33–63. https://doi.org/10.1007/s11145-017-9749-x

Franceschini, S., Bertoni, S., & Facoetti, A. (2021). Manual dexterity predicts phonological decoding speed in typical reading adults. *Psychological Research Psychologische Forschung, 85*(8), 2882–2891. https://doi.org/10.1007/s00426-020-01464-4

Gentner, D. R., Larochelle, S., & Grudin, J. (1988). Lexical, sublexical, and peripheral effects in skilled typewriting. *Cognitive Psychology, 20*(4), 524–548. https://doi.org/10.1016/0010-0285(88)90015-1

Grabowski, J. (2008). The internal structure of university student's keyboard skills. *Journal of Writing Research, 1*(1), 27–52. https://doi.org/10.17239/JOWR-2008.01.01.2

Grabowski, J., & Mathiebe, M. (2018). Teaching perspective taking and coherence generation to improve cross-genre writing skills in secondary grades: A detailed explanation of an intervention. *Journal of Writing Research, 10*(2), 331–356. https://doi.org/10.17239/jowr-2018.10.02.06

Graham, S., Berninger, V., Weintraub, N., & Schafer, W. (2010). Development of handwriting speed and legibility in grades 1–9. *The Journal of Educational Research, 92*(1), 42–52. https://doi.org/10.1080/00220679809597574

Graham, S., & Hebert, M. (2011). Writing to read: A meta-analysis of the impact of writing and writing instruction on reading. *Harvard Educational Review, 81*(4), 710–744. https://doi.org/10.17763/HAER.81.4.T2K0M13756113566

Graham, S., Liu, X., Bartlett, B., Ng, C., Harris, K. R., Aitken, A., Barkel, A., Kavanaugh, C., & Talukdar, J. (2018). Reading for writing: A meta-analysis of the impact of reading interventions on writing. *Review of Educational Research, 88*(2), 243–284. https://doi.org/10.3102/0034654317746927

Grudin, J. T., & Larochelle, S. (1982). *Digraph frequency effects in skilled typing*. Technical report ONR-8201.

Hepner, C., McCloskey, M., & Rapp, B. (2017). Do reading and spelling share orthographic representations? *Evidence from Developmental Dysgraphia. Cognitive Neuropsychology, 34*(3–4), 119. https://doi.org/10.1080/02643294.2017.1375904

James, K. H., & Gauthier, I. (2006). Letter processing automatically recruits a sensory–motor brain network. *Neuropsychologia, 44*(14), 2937–2949. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2006.06.026

Johansson, R., Wengelin, Å., Johansson, V., & Holmqvist, K. (2010). Looking at the keyboard or the monitor: Relationship with text production processes. *Reading and Writing, 23*(7), 835–851. https://doi.org/10.1007/s11145-009-9189-3

Johnston, R., McGeown, S., & Moxon, G. E. (2014). Towards an understanding of how children read and spell irregular words: The role of nonword and orthographic processing skills. *Journal of Research in Reading, 37*(1), 51–64. https://doi.org/10.1111/jrir.12007

Jones, A. C., & Rawson, K. A. (2016). Do reading and spelling share a lexicon. *Cognitive Psychology, 86*, 152–184. https://doi.org/10.1016/j.cogpsych.2016.02.003

Kaiser, M. L., Albaret, J. M., & Doudin, P. A. (2009). Relationship between visual-motor integration, eye-hand coordination, and quality of handwriting. *Journal of Occupational Therapy, Schools, and Early Intervention, 2*(2), 87–95. https://doi.org/10.1080/19411240903146228

Kandel, S., Álvarez, C. J., & Vallée, N. (2006). Syllables as processing units in handwriting production. *Journal of Experimental Psychology: Human Perception and Performance, 32*(1), 18. https://doi.org/10.1037/0096-1523.32.1.18

Kandel, S., Hérault, L., Grosjacques, G., Lambert, E., & Fayol, M. (2009). Orthographic vs. phonologic syllables in handwriting production. *Cognition, 110*(3), 440–444. https://doi.org/10.1016/j.cognition.2008.12.001

Kandel, S., Peereman, R., & Ghimenton, A. (2013). Further evidence for the interaction of central and peripheral processes: The impact of double letters in writing English words. *Frontiers in Psychology, 4*, 729. https://doi.org/10.3389/fpsyg.2013.00729

Kandel, S., Peereman, R., Grosjacques, G., & Fayol, M. (2011). For a psycholinguistic model of handwriting production: Testing the syllable-bigram controversy. *Journal of Experimental Psychology: Human Perception and Performance, 37*(4), 1310–1322. https://doi.org/10.1037/a0023094

Kandel, S., & Perret, C. (2015). How does the interaction between spelling and motor processes build up during writing acquisition? *Cognition, 136*, 325–336. https://doi.org/10.1016/j.cognition.2014.11.014

Kandel, S., & Spinelli, E. (2010). Processing complex graphemes in handwriting production. *Memory and Cognition, 38*(6), 762–770. https://doi.org/10.3758/MC.38.6.762

Kandel, S., & Valdois, S. (2005). The effect of orthographic regularity on children's handwriting production. *Current Psychology Letters. Behaviour, Brain & Cognition, 17*, 3.

Kandel, S., & Valdois, S. (2006a). French and Spanish-speaking children use different visual and motor units during spelling acquisition. *Language and Cognitive Processes, 21*(5), 531–561. https://doi.org/10.1080/01690960500095946

Kandel, S., & Valdois, S. (2006b). Syllables as functional units in a copying task. *Language and Cognitive Processes, 21*(4), 432–452. https://doi.org/10.1080/01690960400018378

Kent, S. C., & Wanzek, J. (2016). The relationship between component skills and writing quality and production across developmental levels: A meta-analysis of the last 25 years. *Review of Educational Research, 86*(2), 570–601. https://doi.org/10.3102/0034654315619491

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software, 82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13

Lambert, E., Kandel, S., Fayol, M., & Espéret, E. (2008). The effect of the number of syllables on handwriting production. *Reading and Writing, 21*(9), 859–883. https://doi.org/10.1007/s11145-007-9095-5

Larochelle, S. (1983). A comparison of skilled and novice performance in discontinuous typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 67–94). Springer. https://doi.org/10.1007/978-1-4612-5470-6_4

Lê, M., Quémart, P., Potocki, A., Gimenes, M., Chesnet, D., & Lambert, E. (2021). Modeling the influence of motor skills on literacy in third grade: Contributions of executive functions and handwriting. *PLoS ONE, 16*(11), e0259016. https://doi.org/10.1371/journal.pone.0259016

Lenth, R. V. (2022). *emmeans: Estimated Marginal Means, aka Least-Squares Means* (R package version 1.7.2).

Logan, G. D., & Crump, M. J. C. (2009). The left hand doesn't know what the right hand is doing. *Psychological Science, 10*, 1296–1300. https://doi.org/10.1111/j.1467-9280.2009.02442.x

Logan, G. D., & Crump, M. J. C. (2011). Hierarchical control of cognitive processes. The case for skilled typewriting. *Psychology of Learning and Motivation—Advances in Research and Theory, 54*, 1–27. https://doi.org/10.1016/B978-0-12-385527-5.00001-2

Logan, G. D., & Zbrodoff, N. J. (1998). Stroop-type interference: Congruity effects in color naming with typewritten responses. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 978–992. https://doi.org/10.1037/0096-1523.24.3.978

Longcamp, M., Anton, J. L., Roth, M., & Velay, J. L. (2003). Visual presentation of single letters activates a premotor area involved in writing. *NeuroImage, 19*(4), 1492–1500. https://doi.org/10.1016/S1053-8119(03)00088-0

Longcamp, M., Anton, J. L., Roth, M., & Velay, J. L. (2005). Premotor activations in response to visually presented single letters depend on the hand used to write: A study on left-handers. *Neuropsychologia, 43*(12), 1801–1809. https://doi.org/10.1016/j.neuropsychologia.2005.01.020

Lüdecke, D. (2021). *sjPlot: Data visualization for statistics in social science.* (R package version 2.8.10). https://cran.r-project.org/package=sjPlot

Magrassi, L., Bongetta, D., Bianchini, S., Berardesca, M., & Arienta, C. (2010). Central and peripheral components of writing critically depend on a defined area of the dominant superior parietal gyrus. *Brain Research, 1346*, 145–154. https://doi.org/10.1016/J.BRAINRES.2010.05.046

Mangen, A., Andal, L. G., Oxborough, G. H., & Bronnick, K. (2015). Handwriting versus keyboard writing: Effect on word recall. *Journal of Writing Research, 7*(2), 227–247. https://doi.org/10.17239/JOWR-2015.07.02.1

Mangen, A., & Velay, J.-L. (2010). Digitizing literacy: Reflections on the haptics of writing. In M. H. Zadeh (Ed.), *Advances in haptics* (pp. 385–402). IntechOpen. https://doi.org/10.5772/8710

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods, 44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

McClurg, P., & Kercher, L. (1989). Keyboarding instruction: A comparison of five approaches. *Journal of Educational Computing Research, 5*(4), 445–458. https://doi.org/10.2190/cqxv-ctnh-xapl-41te

MIUR. (2012). *Decreto Ministeriale 16 novembre 2012, n. 254—Indicazioni nazionali per il curricolo della scuola dell'infanzia e del primo ciclo di istruzione*. https://www.gazzettaufficiale.it/eli/id/2013/02/05/13G00034/sg

MIUR. (2018). *Indicazioni nazionali e nuovi scenari, 22 febbraio 2018—Documento a cura del Comitato Scientifico Nazionale per le Indicazioni Nazionali per il curricolo della scuola dell'infanzia e del primo ciclo di istruzione*. https://www.miur.gov.it/documents/20182/0/Indicazioni+nazionali+e+nuovi+scenari/

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Ostry, D. J. (1983). Determinants of interkey times in typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 225–246). Springer. https://doi.org/10.1007/978-1-4612-5470-6_9

Palmis, S., Danna, J., Velay, J. L., & Longcamp, M. (2017). Motor control of handwriting in the developing brain: A review. *Cognitive Neuropsychology, 34*(3–4), 187–204. https://doi.org/10.1080/02643294.2017.1367654

Pammer, K., Hansen, P., Holliday, I., & Cornelissen, P. (2006). Attentional shifting and the role of the dorsal pathway in visual word recognition. *Neuropsychologia, 44*(14), 2926–2936. https://doi.org/10.1016/j.neuropsychologia.2006.06.028

Perry, C., & Ziegler, J. C. (2018). Beyond the two-strategy model of skilled spelling: Effects of consistency, grain size, and orthographic redundancy. *Quarterly Journal of Experimental Psychology, 57*(2), 325–356. https://doi.org/10.1080/02724980343000323

Pinet, S., Hamamé, C. M., Longcamp, M., Vidal, F., & Alario, F. X. (2015). Response planning in word typing: Evidence for inhibition. *Psychophysiology, 52*(4), 524–531. https://doi.org/10.1111/psyp.12373

Pinet, S., Ziegler, J. C., & Alario, F. X. (2016). Typing is writing: Linguistic properties modulate typing execution. *Psychonomic Bulletin and Review, 23*(6), 1898–1906. https://doi.org/10.3758/s13423-016-1044-3

Pinet, S., Zielinski, C., Alario, F.-X., & Longcamp, M. (2022). Typing expertise in a large student population. *Cognitive Research: Principles and Implications, 7*(1), 77. https://doi.org/10.1186/s41235-022-00424-3

Planton, S., Jucla, M., Démonet, J. F., & Soum-Favaro, C. (2019). Effects of orthographic consistency and word length on the dynamics of written production in adults: Psycholinguistic and rTMS experiments. *Reading and Writing, 32*(1), 115–146. https://doi.org/10.1007/s11145-017-9776-7

Planton, S., Jucla, M., Roux, F. E., & Démonet, J. F. (2013). The "handwriting brain": A meta-analysis of neuroimaging studies of motor versus orthographic processes. *Cortex, 49*(10), 2772–2787. https://doi.org/10.1016/j.cortex.2013.05.011

Poole, D. M., & Preciado, M. K. (2016). Touch typing instruction: Elementary teachers' beliefs and practices. *Computers & Education, 102*, 1–14. https://doi.org/10.1016/J.COMPEDU.2016.06.008

Preminger, F., Weiss, P. L., & Weintraub, N. (2004). Predicting occupational performance: Handwriting versus keyboarding. *American Journal of Occupational Therapy, 58*(2), 193–201. https://doi.org/10.5014/ajot.58.2.193

Purcell, J. J., Jiang, X., & Eden, G. F. (2017). Shared orthographic neuronal representations for spelling and reading. *NeuroImage, 147*, 554–567. https://doi.org/10.1016/J.NEUROIMAGE.2016.12.054

Purcell, J. J., Napoliello, E. M., & Eden, G. F. (2011a). A combined fMRI study of typed spelling and reading. *NeuroImage, 55*(2), 750–762. https://doi.org/10.1016/J.NEUROIMAGE.2010.11.042

Purcell, J. J., Turkeltaub, P. E., Eden, G. F., & Rapp, B. (2011b). Examining the central and peripheral processes of written word production through meta-analysis. *Frontiers in Psychology, 2*, 239. https://doi.org/10.3389/fpsyg.2011.00239

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.r-project.org/

Rapp, B., Epstein, C., & Tainturier, M. J. (2002). The integration of information across lexical and sublexical processes in spelling. *Cognitive Neuropsychology, 19*(1), 1–29. https://doi.org/10.1080/0264329014300060

Rønneberg, V., & Torrance, M. (2019). Cognitive predictors of shallow-orthography spelling speed and accuracy in 6th grade children. *Reading and Writing, 32*(1), 197–216. https://doi.org/10.1007/s11145-017-9751-3

Rønneberg, V., Torrance, M., Uppstad, P. H., & Johansson, C. (2022). The process-disruption hypothesis: How spelling and typing skill affects written composition process and product. *Psychological Research Psychologische Forschung, 86*(7), 2239–2255. https://doi.org/10.1007/S00426-021-01625-Z/FIGURES/4

Roux, S., McKeeff, T. J., Grosjacques, G., Afonso, O., & Kandel, S. (2013). The interaction between central and peripheral processes in handwriting production. *Cognition, 127*(2), 235–241. https://doi.org/10.1016/j.cognition.2012.12.009

Rumelhart, D. E., & Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive-motor performance. *Cognitive Science, 6*(1), 1–36. https://doi.org/10.1016/S0364-0213(82)80004-9

Sahel, S., Nottbusch, G., Grimm, A., & Weingarten, R. (2008). Written production of German compounds: Effects of lexical frequency and semantic transparency. *Written Language & Literacy, 11*(2), 211–227. https://doi.org/10.1075/wll.11.2.06sah

Salthouse, T. A. (1986). Perceptual, cognitive, and motoric aspects of transcription typing. *Psychological Bulletin, 99*(3), 303–319. https://doi.org/10.1037/0033-2909.99.3.303

Sartori, G., Job, R., & Tressoldi, P. E. (2007). *DDE-2. Batteria per la valutazione della dislessia e della disortografia evolutiva-2*. Giunti O.S.

Scaltritti, M., Arfé, B., Torrance, M., & Peressotti, F. (2016). Typing pictures: Linguistic processing cascades into finger movements. *Cognition, 156*, 16–29. https://doi.org/10.1016/j.cognition.2016.07.006

Scaltritti, M., Miniukovich, A., Venuti, P., Job, R., De Angeli, A., & Sulpizio, S. (2019). Investigating effects of typographic variables on webpage reading through eye movements. *Scientific Reports, 9*(1), 1–12. https://doi.org/10.1038/s41598-019-49051-x

Spilling, E. F., Rønneberg, V., Rogne, W. M., Roeser, J., & Torrance, M. (2022). Handwriting versus keyboarding: Does writing modality affect quality of narratives written by beginning writers? *Reading and Writing, 35*(1), 129–153. https://doi.org/10.1007/S11145-021-10169-Y/TABLES/5

Stanovich, K. E., & West, R. F. (1989). Exposure to print and orthographic processing. *Reading Research Quarterly, 24*(4), 402. https://doi.org/10.2307/747605

Statsenko, Y., Habuza, T., Van Gorkom, K. N., Zaki, N., & Almansoori, T. M. (2020). Applying the inverse efficiency score to visual-motor task for studying speed-accuracy performance while aging. *Frontiers in Aging Neuroscience, 12*, 452. https://doi.org/10.3389/fnagi.2020.574401

Suárez-Coalla, P., González-Martín, N., & Cuetos, F. (2018). Word writing in Spanish-speaking children: Central and peripheral processes. *Acta Psychologica, 191*, 201–209. https://doi.org/10.1016/J.ACTPSY.2018.10.001

Sumner, E., Connelly, V., & Barnett, A. L. (2014). The influence of spelling ability on handwriting production: Children with and without dyslexia. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(5), 1441. https://doi.org/10.1037/A0035785

Tainturier, M.-J., & Rapp, B. (2001). The spelling process. In B. Rapp (Ed.), *The handbook of cognitive neuropsychology: What deficits reveal about the human mind* (pp. 263–289). Psychology Press.

Townsend, J. T., & Ashby, F. G. (1978). Methods of modeling capacity in simple processing systems. In J. N. J. Castellan & F. Restle (Eds.), *Cognitive theory* (pp. 199–239). Lawrence Erlbaum Associates.

Van den Bergh, O., Vrana, S., & Eelen, P. (1990). Letters from the heart: Affective categorization of letter combinations in typists and nontypists. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*(6), 1153–1161. https://doi.org/10.1037/0278-7393.16.6.1153

Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10*, 165–191. https://doi.org/10.1016/0167-9457(91)90003-G

Van Selst, M., & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *The Quarterly Journal of Experimental Psychology, 47*(3), 631–650. https://doi.org/10.1080/14640749408401131

van Weerdenburg, M., Tesselhof, M., & van der Meijden, H. (2019). Touch-typing for better spelling and narrative-writing skills on the computer. *Journal of Computer Assisted Learning, 35*(1), 143–152. https://doi.org/10.1111/JCAL.12323

Vandierendonck, A. (2017). A comparison of methods to combine speed and accuracy measures of performance: A rejoinder on the binning procedure. *Behavior Research Methods, 49*(2), 653–673. https://doi.org/10.3758/s13428-016-0721-5

Volman, M. J. M., Van Schendel, B. M., & Jongmans, M. J. (2006). Handwriting difficulties in primary school children: A search for underlying mechanisms. *American Journal of Occupational Therapy, 60*(4), 451–460. https://doi.org/10.5014/ajot.60.4.451

Van Waes, L., Leijten, M., Roeser, J., Olive, T., & Grabowski, J. (2021). Measuring and assessing typing skills in writing research. *Journal of Writing Research, 13*(1), 107–153.

Weigelt-Marom, H., & Weintraub, N. (2015). The effect of a touch-typing program on keyboarding skills of higher education students with and without learning disabilities. *Research in Developmental Disabilities, 47*, 208–217. https://doi.org/10.1016/J.RIDD.2015.09.014

Weigelt-Marom, H., & Weintraub, N. (2018). Keyboarding versus handwriting speed of higher education students with and without learning disabilities: Does touch-typing assist in narrowing the gap? *Computers & Education, 117*, 132–140. https://doi.org/10.1016/J.COMPEDU.2017.10.008

Weingarten, R., Nottbusch, G., & Will, U. (2004). Morphemes, syllables, and graphemes in written word production. In T. Pechmann & C. Habel (Eds.), *Multidisciplinary approaches to language production production* (pp. 529–572). De Gruyter Mouton. https://doi.org/10.1515/9783110894028.529

Weintraub, N., Gilmour-Grill, N., & Weiss, P. L. (2010). Relationship between handwriting and keyboarding performance among fast and slow adult keyboarders. *American Journal of Occupational Therapy, 64*(1), 123–132. https://doi.org/10.5014/ajot.64.1.123

Weintraub, N., & Graham, S. (2000). The contribution of gender, orthographic, finger function, and visual-motor processes to the prediction of handwriting status. *Occupational Therapy Journal of Research, 20*(2), 121–140. https://doi.org/10.1177/153944920002000203

Westfall, J. (2016). *PANGEA: Power ANalysis for GEneral Anova designs*. http://jakewestfall.org/pangea/

Yechiam, E., Erev, I., Yehene, V., & Gopher, D. (2003). Melioration and the transition from touch-typing training to everyday use. *Human Factors, 45*(4), 671–684. https://doi.org/10.1518/hfes.45.4.671.27085

Yeung, P., Ho, C. S., Chan, D. W., & Chung, K. K. (2013). Modeling the relationships between cognitive-linguistic skills and writing in Chinese among elementary grades students. *Reading and Writing, 26*(7), 1195–1221. https://doi.org/10.1007/s11145-012-9411-6

Zhang, Q., & Feng, C. (2017). The interaction between central and peripheral processing in Chinese handwritten production: Evidence from the effect of lexicality and radical complexity. *Frontiers in Psychology, 8*, 334. https://doi.org/10.3389/fpsyg.2017.00334

Ziegler, J. C., Tan, L. H., Perry, C., & Montant, M. (2000). Phonology matters: The phonological frequency effect in written Chinese. *Psychological Science, 11*(3), 234–238. https://doi.org/10.1111/1467-9280.00247

Authors and Affiliations

Tania Cerni[1,3] · **Remo Job**[2,3]

[1] Dipartimento di Psicologia dello Sviluppo e della Socializzazione (DPSS), Università degli Studi di Padova, Via Venezia 8, 35130 Padova, Italy

[2] Dipartimento di Psicologia e Scienze Cognitive, Università di Trento, Corso Bettini, 31, 38068 Rovereto, TN, Italy

[3] Fondazione Marica De Vincenzi ONLUS, Via Manzoni, 11-13, 38068 Rovereto, TN, Italy