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The interaction of central and peripheral processes in typing and handwriting: a direct comparison

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Abstract

This study aims to investigate the interaction between linguistic and peripheral-motor processes in written production. Past research has focused on this topic by analyzing how handwriting and, more recently, typing execution were influenced by lexical and sublexical variables. We take a step further in this study by directly comparing handwriting and typing, examining if different motor executions allow for different flows of linguistic processing. Participants typed and handwrote a set of Italian stimuli in which we manipulated lexicality (words vs pseudowords), orthographic complexity (stimuli with vs without multi-letter graphemes), and length (short vs long stimuli). We measured and analyzed latency (RTs), the difference between RTs and the acoustic duration of the stimuli (RT–AD), mean length of interletter intervals (ILIs), and whole response duration (WRD). We further explored the effects of the position of the orthographic complexity on RTs, RT–AD, ILIs, and WRD. Results suggested a cascaded, continuous processing flow for handwriting and a mixed mechanism involving both serial and parallel modes of processing for typing. The differences in linguistic processing during handwriting and typing suggest different mechanisms in segmenting, maintaining, and retrieving the orthographic representation during motor execution.

Keywords. Cascaded model; Serial model; Writing to dictation; Written production; Motor execution; Linguistic processes

Introduction

The role and interdependence of central and peripheral processes in written production are still open to debate. In writing to dictation, central processes manage the perception and deconstruction of the acoustic input into an ordered sequence of letters –often assumed to be coded in an abstract format (abstract letter identity- ALI)– which constitutes an orthographic representation (e.g., Rapcsak & Beeson, 2002; Rapp et al., 2002; Rapp & Caramazza, 1997). The graphemic buffer, a working memory storage, then temporarily maintains this sequence during the execution of peripheral processes (Caramazza et al., 1987). These latter processes handle the conversion of the abstract letter strings into detailed motor information that is propagated down the motor system (Planton et al., 2013; Purcell et al., 2011).

Central processes are assumed to be common to any production modality, whereas peripheral processes involve different planning and execution mechanisms as a function of whether written production is performed with a pen or a keyboard. Handwriting requires the selection of allographs, their conversion into size and order of strokes, and the effective motor execution of a limb (Teulings et al., 1983; Van Galen et al., 1989). Typing comprises a translation phase, during which the orthographic representation is translated into hand and finger motor commands, and an execution phase in which the typing movements are executed (Rumelhart & Norman, 1982; Salthouse, 1986; Wu & Liu, 2008). The sensory-motor aspects of peripheral processes also differ. Handwritten letters are contingent personal variations of a standard model, whereas typed letters correspond to standard fonts generated by finger taps. In addition, during the planning and execution of handwriting, the attentional focus stays on the top of the pen, while movement regulation contemporarily involves the coordination of ego-centric and allo-centric reference frames (Purcell et al., 2011). Typing in contrast allows for focusing visual attention on the screen, the haptic input (keys), or splitting visual attention and oscillating between both the screen and the keys. The specific limb movements required for typing depend on the position of the keys on the keyboard and, naturally, the speed compared with handwriting differs: handwriting is typically slower. Skilled writers can produce a cursive script at a rhythm of six strokes per second (Van Galen, 1990), whereas a skilled typist can reach a mean interval between keystrokes of 60 ms and 200 words per minute (Rumelhart & Norman, 1982).

There is not yet a proper model of the inter-relationship between central and peripheral processes which takes into account different production modalities. Central and peripheral processes have often been treated as separate and unconnected stages, starting from neuropsychological studies (for a review, see Planton et al., 2013; Purcell et al., 2011). Similarly, handwriting and typing have usually been investigated independently and from different viewpoints, with a focus on psycholinguistics for handwriting and on executive planning for typing (Pinet et al., 2016). The long-established distinction between serial and cascaded models of language processing additionally influences both handwriting and typing related research (see e.g., Damian, 2003; Kello et al., 2000 for oral production; see e.g., Roux et al., 2013; Scaltritti et al., 2016 for written production). Concerning written word production, a *serial* model postulates that cognitive/linguistic processes, involved in the construction of the orthographic representation, do not affect writing/typing execution, being terminated before this execution. If linguistic processes spread into the execution, as they are still active, a *cascaded* flow governs the model. The following paragraphs outlined the manner in which handwriting and typing research contributes to the understanding of the serial or cascaded relationships between central and peripheral processes.

For handwriting, the growing body of studies exploring linguistic effects on different execution measures confirms the influence of central processes on peripheral ones, consistently so for sublexical variables and with mixed results for lexical variables. Sublexical variables such as irregular grapheme-to-phoneme mapping slow down whole word duration (the time taken to write a word, from the first to the last pen press), particularly for words that are infrequent in the lexicon (Delattre et al., 2006; Planton et al., 2019). This slower execution of grapheme-to-phoneme irregularities also emerges from other writing measures, such as single letter duration (Afonso et al., 2015; Kandel et al., 2013; Kandel & Spinelli, 2010; Roux et al., 2013) and interletter interval (ILI, i.e., the time the pen is lifted between two consecutive letters; Afonso et al., 2015; Kandel et al., 2013). As for lexical variables, Roux et al. (2013) reported an effect of lexicality (faster responses to words than to pseudowords) on writing latency (RT – first pen press necessary to initiate writing a stimulus) and on stroke duration, which is faster for letters at initial positions and slower for letters in final positions for pseudowords compared to regular words. However, lexicality showed no effects on ILIs (Kandel et al., 2006). Similar results were found for lexical frequency (i.e., the frequency of a given word in the lexicon, Delattre et al., 2006) which seems to affect writing execution only at the beginning of writing acquisition (Afonso et al., 2018). Despite the absence of stable effects of lexical variables during writing execution, the consistent evidence that sublexical variables affect handwriting movements has led to postulate a cascaded model (see e.g., Kandel et al., 2013; Palmis et al., 2019; Roux et al., 2013).

Regarding typing, linguistic interactions were found on typing latencies (RTs – the time taken to press the first key) but not during typing execution, suggesting that linguistic processing is completed before peripheral processes have started. For example, Baus et al.(2013) tested the effect of lexical frequency on typing production and reported slower RTs for low-frequency words compared to high-frequency words. They did not find any lexical frequency effect on whole word typing duration (the time elapsed between the first and the last keypress of the word) and on interkeystroke intervals (IKIs, the time elapsing between two keypresses). Furthermore, Logan and Zbrodoff (1998), and later Damian and Freeman (2008), found a typical interference effect on typing RTs, but no effect on typing execution during a Stoop color-word test which required participants to type the color name. Taken together, these findings suggest that response execution is separated from earlier processing stages such as linguistic processes, in accordance with a serial model. Similarly, Logan and Crump (2009, 2011) maintained that two encapsulated and hierarchical phases governed typing: an “outer loop”, that extracts words from the input text, and an “inner loop” that translates the words into the corresponding keypresses. According to this model, word-level information causes parallel activation of constituent keystrokes in the outer loop phase, while the “inner loop” handles pure motor execution.

An emerging line of research, which examines typing from a psycholinguistic perspective, has challenged the postulated serial model finding influences of lexical and sublexical factors on typing execution. Word-level variables, such as lexical frequency, semantic transparency (i.e., extent to which the meaning of a word can be derived from its constituent morphemes), orthographic neighborhood size (i.e., the number of words in the lexicon that could be created by changing one letter in a target word), inconsistent phoneme-to-grapheme mapping, and length (i.e., number of letters) were found to affect both latency and IKIs (see e.g., Bloemsaat et al., 2003; Gentner et al., 1988; Pinet et al., 2016; Rønneberg & Torrance, 2019; Sahel et al., 2008; Scaltritti et al., 2016). Regarding sublexical factors, Gentner et al. (1988) found that bigram frequency (the frequency of a particular letter pair in a written lexicon) and syllabic structure affect typing execution. This is because infrequent bigrams, as well as the presence of a syllable boundary, slow down IKIs (see also e.g., Pinet et al., 2016; Weingarten et al., 2004). Regarding lexical variables, Scaltritti et al., (2016) found that in a picture typing task, words with higher lexical frequency and higher name agreement (the degree to which different people agree on a particular name for a particular image) have faster RTs and IKIs, in comparison to words with a lower frequency and lower name agreement. Orthographic neighborhood size affects IKIs but does not affect RTs. According to the authors, this selective effect on IKIs may prove that some aspects of the orthographic representation are processed exclusively during execution, bringing the hierarchical structure proposed by e.g., Logan and Crump (2009, 2011) into question.

The Present Study

Evidence for a cascade model in handwriting production is quite robust, at least examining sublexical processing; for typing the picture is less univocal, with mixed and sometimes inconsistent results. The principal aim of this study was to disentangle the nature of the relationship between central and peripheral processes. This was achieved by directly comparing handwriting and typing on the same set of stimuli while manipulating variables known to affect written language production. Specifically, we manipulated lexicality (word vs pseudowords), the complexity of sound-to-spelling mapping (simple vs complex stimuli), and stimulus length (short vs long stimuli), in dictation tasks performed with both production modalities by Italian-speaking participants. Assuming that linguistic information affects both handwriting and typing execution according to a cascade architecture, we aimed to understand whether the three variables we manipulated affect handwriting and typing in the same manner and to the same extent. Conversely, the absence of linguistic effects during typing execution was considered as a confirmation of serial planning.

From a methodological point of view, one of the greatest challenges was to find production measures that could be examined comparatively in both typing and handwriting. Four measures were selected to explore the effect of linguistic variables both before movement initiation and during movement execution in typing and handwriting tasks. Before movement initiation, we collected RTs and the difference between RTs and the Acoustic Duration of the stimulus (RT–AD). In handwriting, an RT corresponds to the first pen press after stimulus presentation, while in typing it corresponds to the first keypress. Even though the two production modalities require distinct movements to start (i.e., reaching a surface with the pen in handwriting and reaching a key on the keyboard in typing), RTs in both modalities are a proxy of central process loading. The RT–AD measure allowed us to explore the time relationship between the deployment of the acoustic signal and the starting of written production, providing insights into how much sensory information is processed before execution of the motor programs. To explore the extent to which linguistic processing cascade into handwriting and typing peripheral processes, we collected inter-letter interval means (ILIs) and Whole Response Duration (WRD) as measures of written execution. In typing, ILIs correspond to the more commonly called IKIs, which reflect the time elapsed between two keypresses. This time interval comprises the execution of a letter (pressing the key) and the press of the following one. In handwriting, ILIs reflect the time between the moment of lifting the pen out of a letter and the moment of initiating the next (the letter execution time is not part of the measure). Despite the difference, the measure allows detecting the time necessary to select and initiate successive letters. WRD records the time required to write the entire stimulus: from the first to the last pen press in handwriting and from the first to the last keypress in typing. It involves letter execution and pauses between letters in both tasks.

Among the linguistic variables we manipulated, lexicality permitted us to explore whether the activation of a stored vs constructed orthographic representation (words vs pseudowords) modulates response preparation and response execution. As mentioned in the introduction, lexicality showed mixed results in handwriting. The effect on RTs is well documented, but the results on handwriting execution are inconsistent (e.g., Kandel et al., 2006; Lambert et al., 2008; Roux et al., 2013). Typing RTs are generally slower in pseudowords compared to words (Bloemsaat et al., 2003), while for ILIs the effect is not always present (i.e., slowed down ILIs in Massaro & Lucas, 1984; Nottbusch et al., 2005; no results in Grudin & LaRochelle, 1982). In line with a cascaded model, we predicted a slower execution (ILIs and WRD) of pseudowords than words, but also slower RTs and higher RT–AD since constructing a new orthographic representation requires more time than recovering a known one.

Regarding orthographic complexity, the presence of complex graphemes requires solving a conflict either between the outputs of the lexical and sublexical routes (e.g., Houghton & Zorzi, 2003) or between different alternative outputs (e.g., Seidenberg & McClelland, 1989). This conflict resolution increases processing time. Most of the previous writing research on the influence of linguistic processes on peripheral ones explored deep orthographies (mostly French) in which orthographic irregularities are typical. Italian is characterized by a shallow orthography, even if it presents some ambiguities and complexities in mapping phonemes into graphemes. To illustrate, the phonemes [kw] can be spelled as *cu* (e.g., *cuore*, heart) or *qu* (e.g., *quando*, when), and [ce] can be spelled as *ce* (e.g., *cena,* dinner) or *cie* (e.g., *cielo*, sky). Furthermore, Italian has phonemes represented by two graphemes (e.g., [k] – *ch*, [g] – *gh*, [ʃ] – *sc*, [ʎ] – *gli*, [ɲ] – *gn).* Such multi-letter phonemes slow down letter duration in handwriting (Kandel & Spinelli, 2010), while in typing mixed results are reported, but generally, an orthographic complexity affects typing execution (Bloemsaat et al., 2003; Pinet et al., 2016; Rønneberg & Torrance, 2019). In line with these results, we hypothesized to observe slower ILIs and WRD for complex than for simple stimuli.

Length is a valid candidate variable to investigate segmentation processes during production. Evidence from handwriting studies suggests that working memory capacity influences written production, probably due to graphemic buffer storage limitations that force longer items to be rehearsed during production (e.g., Caramazza et al., 1987; Kandel et al., 2011; Lambert et al., 2008; Planton et al., 2019). The number of syllables in a word, as a proxy for length, does not affect latency but alters ILIs which are significantly slower when they correspond to a syllable boundary (Álvarez et al., 2009; Kandel et al., 2006; Kandel & Valdois, 2006; Lambert et al., 2008). According to a cascaded architecture, written production proceeds by segmenting words into smaller chunks corresponding to syllables (Kandel et al., 2011). Similarly, typing models suggest that word length affects ILIs, but not RTs, in typing isolated words (i.e., long items elicit longer typing duration; Sternberg et al., 1978; but see also Scaltritti et al., 2016 for an inverse pattern). Weingarten et al. (2004) proposed that this slowdown could be a side-effect of the "syllables effect" that they found also in typing, that is, longer ILIs at syllable boundaries. Based on the literature, we expected longer ILIs and, of course, longer WRD in long stimuli compared to short stimuli. We did not expect effects of length on RTs but we predicted negative RT–AD in long stimuli, hypothesizing that written response may start when enough information has been processed, without waiting for the end of the acoustic signal and with correlated problems of working memory. Finally, we hypothesized that an orthographic complexity would slow down written execution of both short and long stimuli assuming linguistic processing of stimulus chunks during written production. Similarly, we predicted that short and long pseudowords would slow down execution compared respectively to short and long words. For long items, we did not exclude possible interactions between task, length and lexicality, and between task, length and orthographic complexity, as memory demands in the two tasks could differ, given the very different motor programming mechanisms involved.

This study aimed at understanding if central processes percolate equally on typing and handwriting, considering the same linguistic variables and production measures. Measures collected before movement execution (RTs and RT–AD) allowed us to explore the role of central processes before production. Assuming that central processes affect both typing and handwriting, we expected to observe effects of length, orthographic complexity, and lexicality on execution (WRD and ILIs) of both production modalities.

Materials and Methods

Participants

Thirty-six adults (Female = 21, mean age = 23.58, SD = 2.91) volunteered. We recruited graduate and post-graduate students at the University of Trento, Italy (years of education: mean = 16.94, SD = 1.98). We based our sample size on previous studies, which tested 2- or 3-way interactions between linguistic variables in handwriting on different execution measures (Delattre et al., 2006; Kandel et al., 2013; Planton et al., 2019; Roux et al., 2013). These studies tested 20-30 participants (39 in Kandel et al., 2013) on 28-30 items per condition. As we hypothesized 3-way interactions between production modality (typing vs handwriting) and two linguistic variables, and we planned to test 28 items for each condition of interest, we assumed that 36 participants were a reasonable sample size to reach sufficient power. For confirmation, we performed a sensitivity analysis using PANGEA - Power ANalysis for GEneral Anova designs (Westfall, 2016). We tested our repeated measure design clarifying random variables (participants and stimuli) and the four independent variables we considered (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, while a 4-way interaction between all the variables considered (with 14 items per condition), would reach a power of .98.

None of the participants reported visual or auditory impairments, nor cognitive or language disorders. All of them spoke Italian as their first language, and only one declared to be bilingual (Hungarian L2). For each participant, we measured manual preferences using the Edinburgh Handedness Inventory (Oldfield, 1971). Thirty-three participants were right-handed in handwriting, with a laterality index ranging from .40 to 1.00 (mean = .88, SD = .16). The remaining three participants reported a negative index (–1.0, –.80, –.70), declaring to handwrite with the left hand. All participants typed with two hands and reported using the computer for a mean of 12.53 years (SD = 5.27). Only one participant attended a touch-typing course in the past. To ensure that the participants had typing experience, and to compare their typing and handwriting habits, we collected information on the average time in minutes spent daily in reading and writing on the computer and with pen and paper. Participants reported spending reading on paper for a mean of 222.00 minutes a day (SD = 170.59) and reading on screens for a mean of 275.69 minutes (SD = 228.65). The difference was not significant (paired t-test: $t = 1.37, p = .180$). They reported spending a mean of 170.11 minutes a day in handwriting (SD = 170.64) and a mean of 215.42 minutes in typing (SD = 163.11). The difference was not significant (paired t-test: $t = 1.27$, $p = .213$). 22 participants declared to be more used to typing than handwriting, while the remaining reported the opposite.

We collected informed consent before the experimental session. The study protocol was approved by the Research Ethics Committee of the University of Trento.

Stimuli

One hundred and twelve stimuli were used in the typing task and in the handwriting task (see Tasks and procedure). Half of them were words and half were pseudowords. Stimuli lists are available at: https://osf.io/xfdcv/?view_only=f5cea415bf4349e5a6a0056b37ee49f4.

Word list comprised 56 Italian nouns selected from the *Phonitalia* database (Goslin et al., 2014). Half of the words (N = 28) were short (5-6 letters). They were two-syllable long except for *a-ve-na* (*oat*) and *fa-i-na* (*marten*) that were three-syllable long. The other half were long words (8-9 letters). They were either 3- (N = 11) or 4-syllable (N = 15) long except for *squar-cio* (*gash*; 2 syllables) and *e-du-ca-to-re* (*educator*; 5 syllables). Half of the words in each of the length sets were orthographically "simple", with a 1:1 grapheme to phoneme correspondence, and half were orthographically "complex", with a variety of orthographic complexities present in the Italian language. In detail, we included words in which one phonemes corresponds to two graphemes: [k]- *ch*, [g] - *gh*, [ʃ] - *sc*, [ʎ] - *gl*, [ɲ] – *gn*. We also included orthographic ambiguities: [tʃe] that could be transcribed as both *ce* or *cie*, [ʃe] transcribed as *sce* or less commonly with *scie,* and [kw] that could represent *cu* or *qu.*[1]. Complexity was mostly present at the end of the stimuli: 10 short words and 8 long words had the complexity in the last syllables. The remaining short and long words had the complexity in the initial syllable, except the long words *in-chie-sta (inquest) and mo-sce-ri-no (gnat),* where the complexity is in the second syllable, and *u-si-gno-lo* (*nightingale*), where the complexity is in the third syllable. None of the words contained accented letters or geminates.

We balanced the word list for several linguistic variables: lexical frequency, bigram frequency mean, letter frequency mean, first letter frequency, and orthographic neighborhood size within and between Length (long vs short) and Orthographic Complexity (simple vs complex). Simple and complex words differed in bigram frequency ($F_{(1,52)} = 5.79$, $p = .020$) and in letter frequency ($F_{(1,52)} = 13.48$, $p < .001$); short and long words differed in orthographic neighborhood size ($F_{(1,52)} = 104.99$, $p < .001$). No other significant differences were found. In addition, we controlled two typing constraints between word categories: the first letter position on the keyboard (whether the first letter of the item corresponds to a key on the right side or on the left side of the keyboard) and the percentage of bimanual transition necessary to type the words (calculated as in Cerni, Longcamp, et al., 2016; Cerni, Velay, et al., 2016). We tested handwriting constraints by considering the mean number of strokes per letter in each word (calculated as in Kandel & Spinelli, 2010). The latter measure was

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[1] Moreover, phonemes such as [ʎ] and [ɲ] were considered ambiguous, especially in North-Western Italian pronunciation, and confused respectively with [lj] – transcribed with *li* – and [nj] – transcribed in *ni* (see e.g., Angelelli et al., 2008 and Marinelli et al., 2009)

unbalanced between complex and simple words ($F_{(1,52)} = 5.18$, $p = .027$). See Table 1 for descriptive statistics of the control variables.

Pseudowords were 56 legal strings, matched to the experimental words for all the relevant dimensions. They were created by changing 1 or 2 letters of the existing short words, and 2 or 3 letters of the existing long words. For the complex pseudowords, we maintained the position and the identity of the complexity. To match typing constraints between words and pseudowords, we replaced original word letters with letters from the same side of the keyboard. We maintained also the identity of the first letter except for *usci* (*doors*) - *isci* (pseudoword) and *oche* (*gooses*) - *iche* (pseudoword) to preserve the orthographically complex grapheme. To respect the word syllabic structures, we replaced vowels with vowels and consonants with consonants. Furthermore, we checked bigram frequency mean, letter frequency mean, first letter frequency, and orthographic neighborhood size within and between Length and Orthographic Complexity sets of pseudowords (see Table 1). Simple and complex pseudowords differed in letter frequency mean ($F_{(1,52)} = 5.60$, $p = .022$) and strokes per letter mean ($F_{(1,52)} = 12.54$, $p < .001$), whereas long and short pseudowords differed in orthographic neighborhood size ($F_{(1,52)} = 89.84$, $p < .001$). Finally, we controlled the same variables considering all the 112 stimuli (words and pseudowords together). There was an overall difference between simple and complex stimuli considering bigram frequency ($F_{(1,104)} = 4.50$, $p = .036$; $F_{(1,108)} = 4.50$), number of stroke mean ($F_{(1,108)} = 16.71$, $p < .001$) and letter frequency ($F_{(1,104)} = 18.06$, $p < .001$) and between long and short stimuli considering orthographic neighborhood size ($F_{(1,104)} = 183.17$, $p < .001$).

All the stimuli were recorded by a male Italian native speaker and segmented with Audacity 2.3.3 (Audacity Team, 2019). We tested the difference in the acoustic duration of the registered stimuli between the linguistic variables of interest (Lexicality, Orthographic complexity, and Length). No difference was found, except for the expected difference between short and long stimuli.

Table 1. Mean and standard deviation (in brackets) of the controlled linguistic variables in word and pseudoword lists.

	Words				**Pseudowords**			
	Short		Long		Short		Long	
	Simple	*Complex*	*Simple*	*Complex*	*Simple*	*Complex*	*Simple*	*Complex*
N	14	14	14	14	14	14	14	14
Lexical Frequency	186.86 (309.57)	197.64 (283.16)	166.57 (274.86)	193.29 (314.97)	-	-	-	-
Bigram Frequency Mean	11.46 (0.42)	11.05 (0.41)	11.30 (0.34)	11.22 (0.34)	11.19 (0.48)	11.09 (0.44)	11.12 (0.32)	11.06 (0.43)
Orthographic neighborhood size	26.50 (9.49)	20.36 (10.26)	4.14 (3.06)	2.64 (3.07)	19.93 (11.19)	16.42 (8.68)	0.14 (.36)	0.29 (0.73)
Letter frequency Mean	7.87 (1.03)	6.83 (0.98)	7.51 (0.44)	7.01 (0.48)	7.53 (1.04)	6.86 (1.05)	7.37 (0.55)	7.00 (0.43)
First letter Frequency	4.88 (3.22)	4.56 (2.85)	5.65 (3.08)	4.11 (2.99)	4.88 (3.22)	5.09 (2.85)	5.65 (3.08)	4.11 (3.00)
% manual transitions	50.59 (27.43)	57.74 (21.79)	62.12 (19.63)	50.63 (13.81)	50.59 (27.43)	57.74 (21.79)	62.12 (19.63)	50.63 (13.81)
Acoustic duration (ms)	553.76 (53.32)	532.62 (67.04)	797.46 (95.16)	840.76 (74.18)	552.76 (69.76)	566.64 (103.76)	820.02 (92.01)	878.42 (68.06)
Strokes per letter mean	2.82 (0.32)	2.55 (0.37)	2.75 (0.40)	2.61 (0.33)	2.89 (0.32)	2.34 (0.44)	2.68 (0.31)	2.59 (0.24)

Tasks and procedure

All the participants performed two dictation tasks: the handwriting task and the typing task, with separated blocks of words and pseudowords. The order of the tasks was counterbalanced between participants, half starting with the pen and half with the keyboard. Within each task, half of the participants started with the word list and the other half with the pseudoword list. All participants performed the tasks individually in the presence of the experimenter in a quiet laboratory of the University of Trento. They sat in front of a tablet PC (see Equipment) and were encouraged to take a comfortable position, self-regulating the distance from the screen. No time limits were imposed, but participants were encouraged to write/type fast and accurately each stimulus as they heard it.

In the typing task, on each trial, an auditory stimulus, either a word or a pseudoword, was presented. The participant typed it on the keyboard and, when finished, he/she pressed the Return key to hear the next stimulus. In this way, the end of the trial was self-regulated. As soon as the trail finished, the next one started. The typed letters appeared at the center of the screen. Participants were instructed to avoid the use of the backspace key. The backspace key was not disabled but, to discourage its usage, participants were informed that pressing it would be accounted as an error. Before the beginning of the task, four practice trials ensured that participants understood the procedure and familiarized themselves with the keyboard.

In the handwriting task, the stimuli and the trial structure were the same as the typing task. Participants handwrote in uppercase letters on a line at the center of the screen, using a special pen (see Equipment). To proceed to the next trial, they pressed the pen on a virtual button representing a red arrow placed at the right of the line. Participants were encouraged to lift the pen naturally between letters as commonly done in writing in uppercase. Four practice trials were administered before the task to allow participants to familiarize themselves with the pen on the screen and with the lifting movement between letters. Uppercase letters separated by spaces were used to allow the calculation of interletter intervals (see a similar procedure in e.g., Kandel et al., 2006).

Equipment

All the computerized tasks were presented on a tablet PC Samsung Galaxy Book 12" (refresh rate: 60 Hz) running a 64-bit version of Windows 10 Pro 1903.

For typing, the tablet PC was used in desktop modality, with a customized physical keyboard; for handwriting, the tablet PC was used in tablet modality as a touchscreen device, lying the device horizontally on the top of a desk, as the typical position of a paper to write on. The tablet is furnished with a specific pen suitable for the touchscreen, the *S Pen*, with a small 0.7 mm tip and ergonomically equal to a normal pen. It is powered by a Wacom digitizer and can differentiate 4096 levels of pressure (tested mean sampling frequency: 240 Hz).

Stimulus presentation and response recordings were controlled by the software OpenSesame 3.2.7 (Mathôt et al., 2012) in the typing task and by the software Eye and Pen 3.0.0-13 (Alamargot et al., 2006) in the handwriting task. Stimuli were presented through headphones.

Statistical Analysis

During the experimental tasks, we collected four chronometric measures used as dependent variables in separate analyses. The first two measures detected information at the onset of written execution: (1) latency (or RTs), i.e., the time taken to press the first letter key/to do the first pen press from the start of the acoustic stimulus; (2) RT–AD, i.e., the difference between the RT and acoustic duration (AD) for each stimulus. The last two measures were collected during execution of the stimuli: (3) whole response duration (WRD), i.e., the time taken to write the whole stimulus, from the first to the last keypress/pen press, and (4) the mean duration of interletter intervals (ILIs), i.e., the mean of the intervals between two consecutive letters. In typing, an ILI corresponded to the time interval elapsed between two consecutive keypresses within the stimulus, while in handwriting each ILI was considered as the duration of a pen lift (pen pressure = 0) between two consecutive letters. In the case there was not a pen lift between two letters (the participant attached two consecutive letters), we assigned it a value of 0 and counted it in the ILI mean. The ILIs were manually computed by the first author by exporting all the pen lifts captured by the software and eliminating lifts within letters. To check the reliability of the measures, a second rater independently analyzed 28.57% of the data, equally distributed between participants, words, and pseudowords. The inter-rater reliability (Cohens' kappa) was .94.

Before the analysis, we discarded as errors 5.93% of the trials in the handwriting task and 9.72% in the typing task (7.82% of all the data). We considered as errors all the orthographically misspelled stimuli. In addition, in typing, we discarded all the stimuli that contained a backspace press, while in handwriting we discarded all the stimuli corrected by the participant during writing (e.g., when the participant went back with the pen to correct letters). We accepted as correct complex pseudowords with the ambiguous phoneme [kw] written as *cu/qu* or [ɲ] written *gn*/*ni* as they are orthographically plausible. We did not accept other ambiguous transcriptions, such as addition or subtraction of one letter from a multi-letter grapheme (e.g., [ʎ] written as *li*). This happened sporadically only for two items.

We also performed outliers' identification and removal for each dependent variable (3.13% for RTs[2], 2.11% for IKIs, and 1.09% for WRD) using the modified recursive procedure with moving criterion (Van Selst & Jolicoeur, 1994). The final datasets are available at https://osf.io/xfdcv/?view_only=f5cea415bf4349e5a6a0056b37ee49f4.

All the statistical analyses were performed in R (version 3.5.0; R Core Team, 2021) using linear mixed-effect models (*lmerTest* package, version 3.1-3; Kuznetsova et al., 2017). The dependent variables were log-transformed to better approximate normal distribution and to meet model assumptions. Given that several RT–AD data-points turned out to be negative, before log-transformation, we calculated a constant (i.e., 1–min(RT) = 561.56) and added it to each RT–AD.

As fixed factors, we considered Lexicality (words vs pseudowords), Orthographic Complexity (complex vs simple), Length (short vs long), and Task (handwriting vs typing), and all the interactions between these factors. We considered as control predictors linguistic variables that were not balanced between the stimuli (bigram frequency, orthographic neighborhood size, strokes per letter mean and mean letter frequency) and task-dependent variables (Trail number and Task Order, i.e., typing or handwriting as the first task). All continuous predictors were scaled before fitting the models. In each model, we allowed random intercepts and random slopes to vary by participants and stimuli. However, due to failure of convergence during model selection or over-parameterization, we finally allowed only random intercepts (Bates et al., 2015; Matuschek et al., 2017).

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[2] RT dataset were the same used for RT–AD analysis

Final models reported in the result section were derived by a stepwise backward elimination procedure, excluding those fixed effects that failed to reach significance using Satterthwaite's method. We started from the higher-order 4-way interaction (Lexicality*Orthographic Complexity*Length*Task) and proceeded backward to evaluate lower-order interactions in case of failure of significance. Following the principle of marginality, we retained in the models all the lower-order interactions and single predictors included in significant higher-order interactions. We considered as significant *t*-values higher than 1.96. We computed lower and upper 95% confidence intervals calculated by subtracting/adding [1.96*standard error] to the estimate of the model predictors. For completeness, we reported *p* values obtained via Satterthwaite's approximation. For significant interactions, we provided pairwise contrasts on estimated marginal means with Tukey adjustment, separately for typing and handwriting, calculated through *emmens* package (version 1.5.4; Lenth et al., 2019). For each higher-order interaction in the final models, we obtained graphical representations of the estimated marginal means and Standard Error (SE) bars through *effects* package (version 4.2.0, Fox & Weisberg, 2019) and *ggplot2* package (version 3.3.5; Wickham, 2016).

Results

Latency (RTs)

Table 2 lists the parameters of the final model. Figure 1 reports the graphical representation of significant higher-order interactions.

RTs were affected by Task. Overall, RTs in handwriting were faster than in typing. A significant interaction between Task and Lexicality suggested that the difference in starting to write words and pseudowords was greater in typing compared to handwriting (pairwise contrasts: handwriting $t_{pw-w} = 2.84$, $p = .005$, typing $t_{pw-w} = 7.27$, $p < .001$). Furthermore, the interaction between Length and Lexicality showed that Length affected only pseudowords, with long pseudowords being initiated more slowly than short ones ($t_{long\,pw-short\,pw} = 2.43$, $p = .015$; $t_{long\,w-short}$

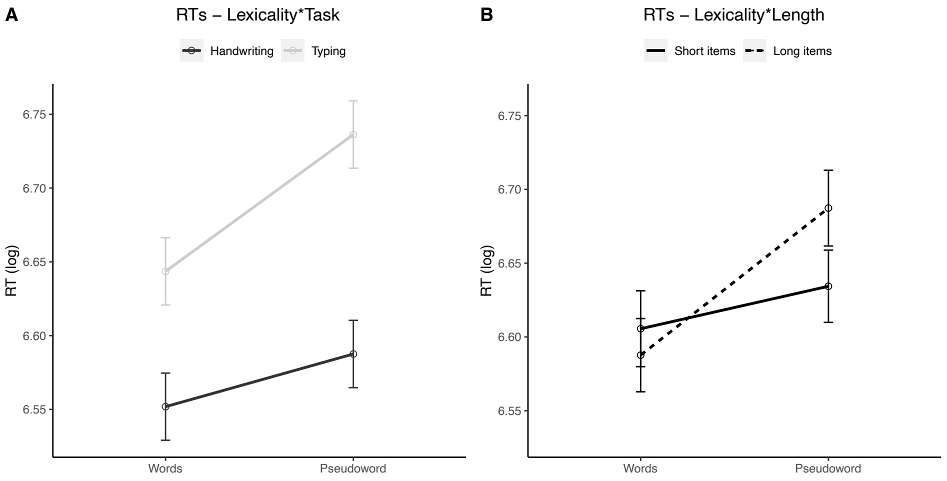
$_w$= 0.78, p = .432). Orthographic complexity did not improve model fit, showing that it did not affect RTs in either task. Other parameters and interactions not listed in Table 2 did not reach significance.

Table 2. Results of the mixed-model analysis on RTs

Random effects	**Variance**	**St. dev.**			
Participants	0.016	0.126			
Items	0.003	0.056			
Residuals	0.037	0.192			
Fixed effects	**Estimate**	**Lower CI**	**Upper CI**	***t***	***p***
Intercept	6.561	6.510	6.611	253.460	< .001
Trial Order	–0.017	–0.021	–0.013	–7.442	< .001
Orthographic N size	–0.044	–0.063	–0.025	–4.477	< .001
Length	–0.018	–0.062	0.026	–0.785	ns
Lexicality	0.001	–0.033	0.034	0.049	ns
Task	0.092	0.079	0.104	14.458	< .001
Length*Lexicality	0.071	0.026	0.116	3.073	.003
Lexicality*Task	0.057	0.039	0.075	6.285	< .001

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

Figure 1. Graphical representation of the significant higher-order interactions in RT analysis



Note. Log-transformed RTs for the interaction between Lexicality and Task (panel A) and for the interaction between Lexicality and Length (panel B). Error bars show standard errors.

Difference between RTs and Acoustic duration (RT–AD)

Table 3 reports rough RT–AD to help in interpreting the findings. Table 4 lists the parameters of the final model.

The main effect of Length and Task were significant, as well as the lower-order interactions between Lexicality and Task, and between Length and Task. A higher-order interaction between Length, Lexicality and Task qualified lower terms. Pairwise comparisons revealed that, in handwriting, words and pseudowords were initiated with a similar time distance from the offset of the acoustic signal ($t_{\text{short pw} - \text{short w}} = 0.14$, $p = .999$; $t_{\text{long pw} - \text{long w}} = 1.52$, $p = .430$). In typing, a difference existed only considering long stimuli ($t_{\text{short pw} - \text{short w}} = 1.16$, $p = .651$; $t_{\text{long pw} - \text{long w}} = 4.33$, $p < .001$). Considering the difference elicited by Length, short stimuli were always initiated after the end of the acoustic signal, while long stimuli were initiated before that signal. This was true in both tasks, but with the exception of typed long pseudowords, which were the only long items started after the end of the acoustic signal (Handwriting: $t_{\text{short w} - \text{long w}} = 11.74$, p < .001; $\text{t}_{\text{short pw} - \text{long pw}} = 10.03$, p < .001; Typing: $t_{\text{short w} - \text{long w}} = 10.17$, $p < .001$; $t_{\text{short pw} - \text{long pw}} = 6.97$, $p < .001$). No other parameters or interactions reached significance.

Table 3. Mean and Standard Deviation (SD) in ms of RT–AD for handwriting and typing depending on lexicality (words and pseudowords) and length (short and long).

		Handwriting		**Typing**	
		Mean	SD	Mean	SD
Words	**Short**	155.04	192.43	217.90	161.92
	Long	–77.88	212.31	–20.30	175.92
Pseudowords	**Short**	157.10	218.07	258.13	190.78
	Long	–45.97	257.22	77.56	228.45

Table 4. Results of the mixed-model analysis on RT–AD

Random effects	**Variance**	**St. dev.**			
Participants	0.028	0.166			
Items	0.019	0.140			
Residuals	0.081	0.284			
Fixed effects	**Estimate**	**Lower CI**	**Upper CI**	***t***	***p***
Intercept	6.541	6.465	6.618	166.119	< .001
Trial Order	–0.023	–0.030	–0.017	–6.915	< .001
Length	–0.464	–0.541	–0.387	–11.735	< .001
Lexicality	–0.006	–0.083	0.071	–0.143	ns
Task	0.096	0.070	0.122	7.230	< .001
Length*Lexicality	0.066	–0.043	0.175	1.176	ns
Lexicality*Task	0.052	0.015	0.089	2.752	.006
Length*Task	0.061	0.024	0.097	3.232	.001
Length *Lexicality*Task	0.060	0.008	0.113	2.244	.025

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

Interletter Interval Mean (ILIs)

Table 5 shows the parameters of the final model. Figure 2 reports the graphical representation of significant higher-order interactions.

The main parameters that yielded significant effects in the final model were Task, Lexicality and Orthographic complexity, while Length did not. The mean length of ILIs was grater in typing than in handwriting, for pseudowords than for words, and for complex than for simple stimuli.

The low-order interactions between Orthographic complexity and Task and between Length and Task yielded additive effect to the model. These lower-order terms were qualified by two higher-order interactions. First, we found a three-way interaction between Lexicality, Length and Task (see Figure 2, panel A). Looking at pairwise contrasts, a length effect emerged only for pseudowords. In typing, long pseudowords elicited longer ILI than short ones ($t_{long\ w-short\ w} = 1.38$, $p = .516$; $t_{long\ pw-short\ pw} = 6.61$, $p < .001$), while in handwriting the pattern was reversed as long pseudowords elicited shorter ILIs ($t_{long\ w-short\ w} = -2.43$ $p = .077$; $t_{long\ pw-short\ pw} = -2.60$, $p = .048$). Considering Lexicality for each combination of Length, pseudowords elicited longer ILIs than words in handwriting, whereas in typing the same effect was present for long stimuli, but there was not a significant effect for short stimuli (Handwriting: $t_{short\ pw-short\ w}$: 4.40, $p < .001$, $t_{long\ pw-long\ w}$: 4.30, $p < .001$; Typing: $t_{short\ pw-short\ w}$: 2.15, $p = .142$, $t_{long\ pw-long\ w}$: 8.69, $p < .001$).

The higher-order interaction between Orthographic complexity, Length, and Task proved significant (see Figure 2, panel B). Contrasts revealed that, in handwriting, complex stimuli elicited significantly longer ILIs than simple stimuli, whit a larger effect for short than for long stimuli ($t_{complex\ short-simple\ short}$: 4.35, p < .001; $t_{complex\ long-simple\ long}$: 3.16, $p = .010$). In typing, the pattern was analogous considering long stimuli but it did not reach significance ($t_{complex\ long-simple\ long}$: 2.37, $p =$

.085), while complex and simple short stimuli elicited equal ILIs ($t_{complex\ short\ –\ simple\ short}$: .51, p = .957). Looking at the difference of Length for each combination of Orthographic complexity, contrasts showed that length strongly affected ILIs in typing, the trend being accentuated for complex stimuli ($t_{simple\ long\ –\ simple\ short}$ = 2.74, p = .034, $t_{complex\ long\ –\ complex\ short}$ = 5.20, p < .001). In contrast, in handwriting ILIs was affected by length only in complex stimuli in the opposite direction compared to typing, indicating that short complex stimuli had slower ILIs than long complex stimuli ($t_{simple\ long\ –\ simple\ short}$ = –1.98, p = .200, $t_{complex\ long\ –\ complex\ short}$ = –3.08, p = .013). No other parameters or interactions were significant.

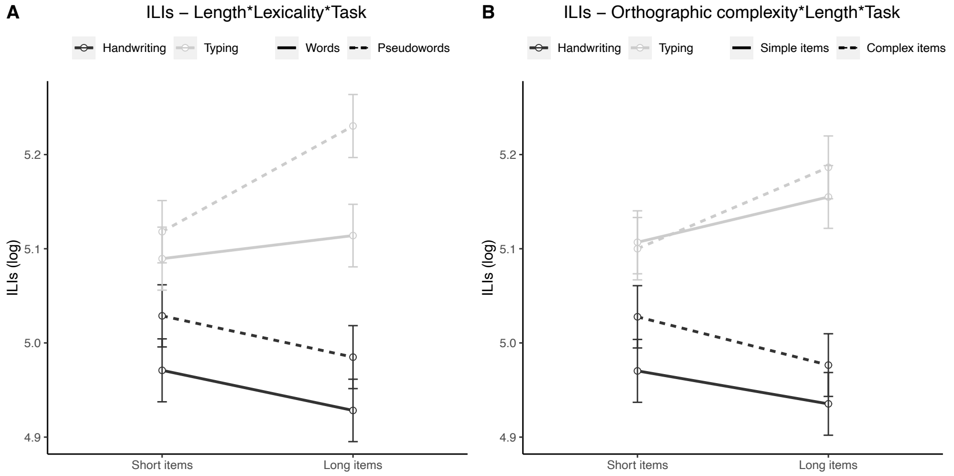
Table 5. Results of the mixed-model analysis on the ILIs

Random effects	**Variance**	**St. dev.**			
Participants	0.036	0.189			
Items	0.001	0.027			
Residuals	0.054	0.232			
Fixed effects	**Estimate**	**Lower CI**	**Upper CI**	***t***	***p***
Intercept	4.942	4.875	5.009	144.332	< .001
Trial Order	–0.019	–0.024	–0.013	–6.872	< .001
Bigram frequency mean	–0.015	–0.024	–0.007	–3.523	< .001
Orth. neighborhood size	–0.028	–0.042	–0.014	–3.882	< .001
Orthographic complexity	0.057	0.032	0.083	4.355	< .001
Length	–0.034	–0.073	0.004	–1.702	ns
Lexicality	0.058	0.033	0.083	4.401	< .001
Task	0.151	0.125	0.177	11.442	< .001
Orthographic complexity*Length	–0.016	–0.052	0.020	–0.879	ns
Orthographic complexity*Task	–0.064	–0.094	–0.034	–4.214	< .001
Length*Lexicality	–0.001	–0.036	0.034	–0.067	ns
Length*Task	0.040	0.003	0.076	2.130	.033

Lexicality*Task	–0.029	–0.059	0.001	–1.918	ns
Length*Lexicality*Task	0.089	0.046	0.132	4.086	< .001
Orthographic complexity*Length*Task	0.054	0.012	0.097	2.502	.012

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

Figure 2. Graphical representation of the significant higher-order interactions in ILI analysis



Note. Log-transformed ILIs for the interaction between Length, Lexicality and Task (panel A), and for the interaction between Orthographic complexity, Length and Task (panel B). Error bars show standard errors.

Whole Response Duration (WRD)

Table 6 reports the parameters of the final model. Figure 3 reports the graphical representation of significant higher-order interactions.

The main effects of interest that improved the final model were Task and Length. As expected, handwriting was slower than typing and long items increased WRD. The lower-order interactions between Orthographic complexity and Task, Lexicality and Task, Length and Task reached significance.

Two higher-order interactions were retained in the final model and qualified lower terms. The interaction between Length, Lexicality, and Task (see Figure 3, panel A) suggested that long items were produced more slowly than short ones in both tasks, more strongly so for pseudowords, with the difference being accentuated in typing (Handwriting: $t_{long\ w - short\ w} = 11.55$, $p < .001$, $t_{long\ pw - short\ pw} = 12.99$, $p < .001$; Typing: $t_{long\ w - short\ w} = 17.44$ p<.001, $t_{long\ pw - short\ pw} = 21.53$, $p < .001$). Looking at the difference of Lexicality for each combination of Length and Task, long pseudowords were typed significantly more slowly than long words ($t_{long\ pw - long\ w} = 4.15$ $p < .001$) but no difference was found in handwriting ($t_{long\ pw - long\ w} = -0.09$, $p = 1.000$). In both tasks, lexicality did not affect short items (Handwriting: $t_{short\ pw - short\ w} = -1.20$, $p = .627$; Typing: $t_{short\ pw - short\ w} = -0.10$, $p = 1.000$).

The interaction between Orthographic complexity, Length, and Task was significant (see Figure 3, panel B). Considering Length for each level of Orthographic complexity and Task, long items elicited longer WRD than short items, the difference being greater in typing than in handwriting (Handwriting: $t_{simple\ long - simple\ short} = 11.08$, $p < .001$, $t_{complex\ long - complex\ short} = 13.37$, $p < .001$; Typing: $t_{simple\ long - simple\ short} = 18.59$, $p < .001$, $t_{complex\ long - complex\ short} = 20.08$, $p < .001$). In both the tasks and independently from Length, the presence of an orthographic complexity did not statistically alter the WRD, but numerically the difference between complex and simple stimuli presented opposite signs in the two tasks and was more accentuated in typing (Handwriting: $t_{complex\ short - simple\ short} = -1.20$, $p = .628$; $t_{complex\ long - simple\ long} = -0.29$, $p = .992$; Typing: $t_{complex\ short - simple\ short} = 2.26$, p = .113; $t_{complex\ long - simple\ long} = 2.09$, $p = .162$).

Table 6. Results of the mixed-model analysis on WRD

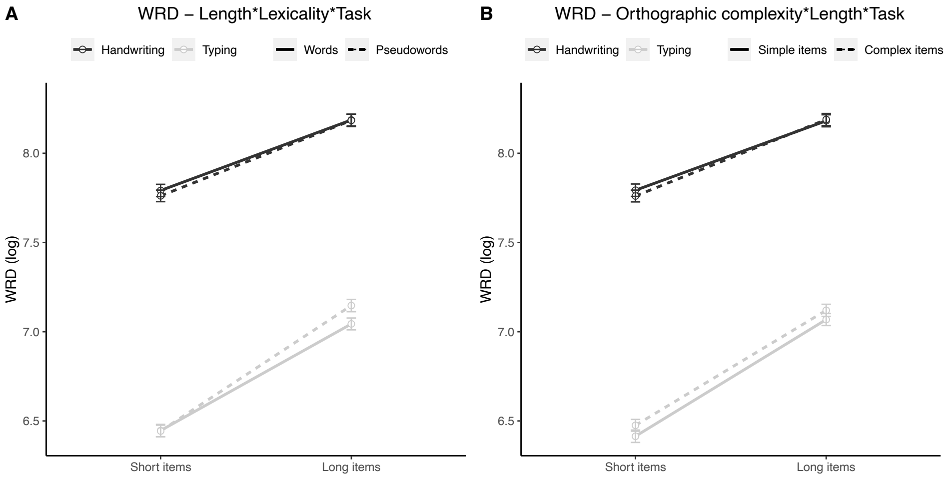
Random effects	**Variance**	**St. dev.**
Participants	0.025	0.159
Items	0.007	0.085

Residuals	0.036	0.190

Fixed effects	**Estimate**	**Lower CI**	**Upper CI**	***t***	***p***
Intercept	7.808	7.733	7.881	204.748	< .001
Trial Order	–0.016	–0.020	–0.012	–7.228	< .001
Orth. neighborhood size	–0.140	–0.169	–0.113	–9.588	< .001
Strokes per letter mean	0.072	0.055	0.090	7.890	< .001
Orthographic complexity	–0.132	–0.084	–0.019	–1.201	ns
Length	0.375	0.299	0.452	9.401	< .001
Lexicality	–0.030	–0.078	0.018	–1.202	ns
Task	–1.392	–1.413	–1.371	–129.863	< .001
Orthographic complexity*Length	0.039	0.029	0.107	1.108	ns
Orthographic complexity*Task	0.094	0.069	0.118	7.548	< .001
Length*Lexicality	0.028	–0.038	0.094	0.810	ns
Length*Task	0.227	0.197	0.257	14.944	< .001
Lexicality*Task	0.028	0.003	0.052	2.238	.025
Length*Lexicality*Task	0.077	0.043	0.112	4.374	< .001
Orthographic complexity*Length*Task	–0.049	–0.084	–0.014	–2.763	.006

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

Figure 3. Graphical representation of the significant higher-order interactions in WRD analysis



Note. Log-transformed WRD for the interaction between Length, Lexicality, and Task (panel A), and for the interaction between Orthographic complexity, Length, and Task (panel B). Error bars show standard errors.

Summary of the main findings

Table 7 summarizes the main findings. Lexicality affected RTs, that is starting a pseudoword took a longer time than starting a word, and the effect was significantly stronger in typing than in handwriting. Length and orthographic complexity did not affect RTs per se, but interacted with lexicality, showing that long pseudowords required more time in starting the handwriting and typing movements. RT–AD, the second measure we selected to detect central processes before written execution, added the following information. For short items, the production movement in both modalities started after the end of the acoustic stimulus for both words and pseudowords. For long items, handwriting started before the end of the acoustic stimulus for both words and pseudowords, while typing started before the end of the acoustic stimulus for words, but after the end of the acoustic stimulus for pseudowords.

Lexicality, orthographic complexity, and length affected movement execution, suggesting that not all linguistic information was exhaustively processed before starting to handwrite and type. Both lexicality and orthographic complexity interacted with length and task. These 3-way interactions suggested interesting differences between typing and handwriting during execution. In handwriting, all the variables considered affected ILIs. Indeed, pseudowords and complex items elicited slower ILIs respectively than words and simple items. Contrary to the expectation, long items elicited faster ILIs than short items, but significantly only for complex items and pseudowords. In typing, the lexicality effect was present only in long stimuli, while orthographic complexity did not affect ILIs. The length effect (i.e., slower execution for long than for short items) was present for pseudowords and in both simple and complex stimuli. This result pattern was similar looking at WRD, even if in handwriting the effects of lexicality and orthographic complexity did not reach significance.

Table 7. Summary of the main results on dependent variables as a function of linguistic variables and task.

		Lexicality	**Orthographic complexity**	**Length**
Handwriting	***RT***	W < Pw	Complex = Simple	Long w = Short w Long pw < Short pw
	RT–AD	W = Pw	Complex = Simple	Long > Short
	ILIs	W < Pw	Complex > Simple	Long w = Short w Long pw < Short pw Long simple = Short simple Long complex < Short complex
	WRD	W = Pw	Complex = Simple	Long > Short
Typing	***RT***	W < Pw	Complex = Simple	Long w =Short w Long pw > Short Pw
	RT–AD	short W = short Pw long W < long Pw	Complex = Simple	Long > Short
	ILIs	short W = short Pw long W < long Pw	Complex = Simple	Long w = Short w Long pw > Short pw Long simple/complex > Short simple/complex
	WRD	short W = short Pw Long W < Long Pw	Complex = Simple	Long > Short

Note. “>” indicates that the dependent variable had a higher value in the first condition of the linguistic variables than in the second condition. “<” indicates that the dependent variable had a lower value in the first condition of the linguistic variables than in the second condition. The “=” symbol corresponds to the absence of a significant effect (i.e., equal value of the dependent variable between the item conditions). When the interactions with length is not specified, long and short items showed similar results. W = Words, Pw = Pseudowords.

Further Analyses on the Position of the Orthographic Complexity

We present in this section further explorative analyses we performed to pinpoint the effect of orthographic complexity, which turned out to be not as clear as we predicted. Intriguingly, in typing, the complexity affected neither the time necessary to initiate the response nor the typing execution. In handwriting the effect was observed considering ILIs but it disappeared when considering letter execution in WRD. We looked again at the data by splitting the complex stimuli into two classes as a function of the position of the irregularity: initial or final. As previously documented, the position of an irregularity affected handwriting (e.g., latency and writing velocity in Planton et al., 2019; letter stroke duration in Roux et al., 2013; latency and letter stroke duration in Palmis et al., 2019), but no specific investigation was done for typing, except considering only portions of the typed stimuli (i.e., syllables in Pinet et al., 2016). Assuming that written execution starts as soon as enough information has been accrued, in accordance with a cascade architecture (Kandel et al., 2011) an initial complexity should be processed before execution, slowing down RTs and possibly RT–AD, while a final complexity would be processed during execution, affecting ILIs and WRD.

To start the analysis, we took out from the pool of data those stimuli with the complexity in the middle position (3 words and the corresponding 3 pseudowords). The remaining complex stimuli (n = 106) had the complexity in the first syllable (Initial) or in the last one (Final).

Models’ construction and selection followed the same rationale as the main analysis. For the sake of simplicity, given that we did not find any significant interaction between Lexicality and

Orthographic complexity, we used Lexicality as a covariate in the models avoiding interactions[3]. In the following description of the models, we reported results of the F-tests on the fixed effects (F-tests and p-values using Satterthwaite's method) for the variables of interest (Complexity Position: Initial, Final, Simple), their relevant interactions and pairwise contrasts. For the complete models, see Supplementary Materials, Table A.

Latency (RTs)

The main effect of Complexity Position was significant ($F = 31.91$, $p < .001$) and was qualified by the interaction between Complexity Position and Length ($F = 6.86$, $p = .002$). Contrasts revealed that, considering long stimuli, an initial complexity slowed down RTs compared to simple stimuli ($t_{\textit{simple long – initial long}} = –6.81$, $p < .001$), while a final complexity did not alter latency ($t_{\textit{simple long – final long}} = –1.45$, $p = .697$). A final complexity elicited shorter RTs than an initial complexity ($t_{\textit{initial long – final long}} = 7.29$, $p < .001$). For short stimuli, the pattern was similar but not significant ($t_{\textit{simple short – initial short}} = –2.11$, $p = .289$; $t_{\textit{simple short – final short}} = 2.73$, $p = .080$). However, the presence of an initial complexity significantly slowed down RTs compared to stimuli with the complexity in the final position ($t_{\textit{initial short – final short}} = 3.99$, $p = .002$). No task difference was found. Figure 4, panel A reports the graphical representation of the significant higher-order interaction.

Difference between RTs and Acoustic duration (RT–AD)

The main effect of Complexity Position and its interaction with Task were significant ($F = 3.24$, $p = .043$ and $F = 4.16$, $p = .016$). The lower-order terms were qualified by a three-way interaction between Complexity Position, Length, and Task ($F = 4.98$, $p = .007$). In handwriting, post hoc contrasts revealed that there were no statistical differences between simple stimuli and

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[3] We performed also the models starting with the four-way interaction Lexicality*Length*Complexity Position*Task. After model reduction, we found the same significant terms and interactions as the models in the main analysis. Importantly, no interactions between Complexity Position and Lexicality (and Length) was found. In general, the results were in line to what we reported in this section.

complex stimuli ($t_{simple\ short - initial\ short} = -1.14$, $p = .864$, $t_{simple\ short - final\ short} = 0.06$, $p = 1.00$; $t_{simple\ long - initial\ long} = 0.67$, $p = .985$, $t_{simple\ long - final\ long} = 2.37$, $p = .177$). In typing, the same pattern was true considering short items ($t_{simple\ short - initial\ short} = -0.96$, $p = .930$, $t_{simple\ short - final\ short} = 0.18$, $p = 1.00$). However, for long items, simple stimuli and stimuli with an initial complexity were started later with respect to the acoustic signal than did the stimuli with a final complexity, which were the only items starting prior to the end of that signal ($t_{simple\ long - initial\ long} = -0.98$, $p = .924$, $t_{simple\ long - final\ long} = 2.94$, $p = .045$, $t_{initial\ long - final\ long} = 2.84$, $p = .059$). See Table 8 for information on the row data.

Table 8. Mean and Standard Deviation (SD) in ms of RT–AD for handwriting and typing depending on Complexity Position (simple, final complexity, and initial complexity) and length (short and long).

		Handwriting		**Typing**	
		Mean	SD	Mean	SD
Simple	**Short**	145.23	180.60	231.45	158.27
	Long	–50.23	239.23	45.25	210.83
Initial complexity	**Short**	204.18	220.03	281.84	205.75
	Long	–45.46	244.20	108.74	251.76
Final complexity	**Short**	152.68	228.83	230.32	189.31
	Long	–99.28	216.05	–26.00	188.40

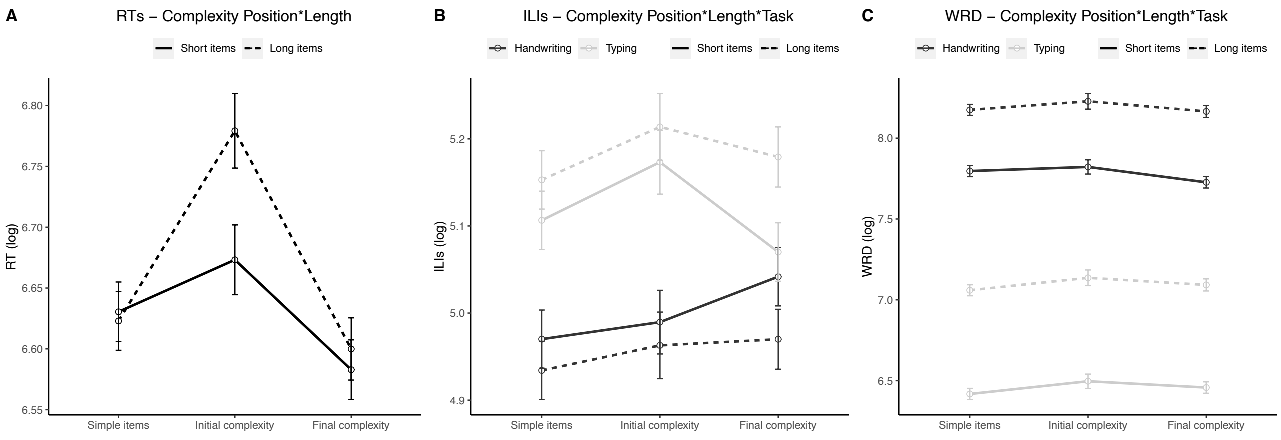
Interletter Interval Mean (ILIs)

The main effect of Complexity Position was significant ($F = 7.65$, $p < .001$) as well as its interaction with Task ($F = 18.16$, $p < .001$). Both the lower-order terms were qualified by a three-way interaction between Complexity Position, Length and Task ($F = 9.23$, $p < .001$). Figure 4, panel B shows a graphical representation of this interaction. Considering the difference in the Complexity Position for each combination of Length, typing and handwriting showed opposite trends in ILIs execution. In handwriting, ILIs were slowed down by a final complexity, particularly in short stimuli ($t_{\text{simple short – initial short}} = -0.99$, $p = .922$, $t_{\text{simple short – final short}} = -4.77$, $p < .001$). No significant difference was found for long stimuli, even if the trend looked similar ($t_{\text{simple long – initial long}} = -1.24$, $p = .815$, $t_{\text{simple long – final long}} = -2.30$, $p = .198$). In typing, the initial complexity slowed down ILIs, particularly in short stimuli, compared to regular stimuli and to stimuli with a final complexity ($t_{\text{simple short – initial short}} = -3.32$, $p = .013$, $t_{\text{simple short – final short}} = 2.39$, $p = .165$). No statistical difference was found in long stimuli, even if the trend looked similar ($t_{\text{simple long – initial long}} = -2.60$, $p = .102$; $t_{\text{simple long – final long}} = -1.66$ $p = .562$).

Whole Response Duration (WRD)

The main effect of Complexity Position was not significant but its interaction with Task was significant ($F = 28.50$, $p < .001$) and qualified by a higher-order interaction between Complexity Position, Length and Task ($F = 5.45$, $p = .004$). Figure 4, panel C shows a graphical representation of this interaction. Considering the difference between Complexity Positions for each level of Length, no statistical differences were found nor in typing nor in handwriting. Nevertheless, considering short stimuli, the interactions confirmed that in typing an initial complexity tended to slow down WRD, as found in ILI analysis ($t_{\text{simple short – initial short}} = -2.11$, $p = .291$; $t_{\text{simple short – final short}} = -1.25$, $p = .811$), while in handwriting a final complexity accelerated writing movements, suggesting that letter execution was speeded up in comparison to slower ILIs ($t_{\text{simple short – initial short}} = -0.68$, $p = .983$; $t_{\text{simple short – final short}} = 2.20$, $p = .249$). Even though the effects were quite flat, this tendency was attenuated for long stimuli in typing ($t_{\text{simple long – initial long}} = -1.83$, $p = .449$; $t_{\text{simple long – final long}} = -1.12$, $p = .872$) while in handwriting an initial complexity slightly increased the writing duration and a final complexity did not alter WRD in comparison to simple stimuli ($t_{\text{simple long – initial long}} = -1.26$, $p = .805$; $t_{\text{simple long – final long}} = 0.33$, $p = .999$).

Figure 4. Graphical representation of the significant higher-order interactions in RT (panel A), ILI (panel B) and WRD (panel C) analyses on Complexity Position.



Note. Panel A shows the log-transformed RTs for the interaction between Complexity Position and Task. Panel B shows the log-transformed ILIs for the interaction between Complexity Position, Length and Task. Panel C shows the log-transformed WRD for the interaction between Complexity Position and Task. Error bars show standard errors.

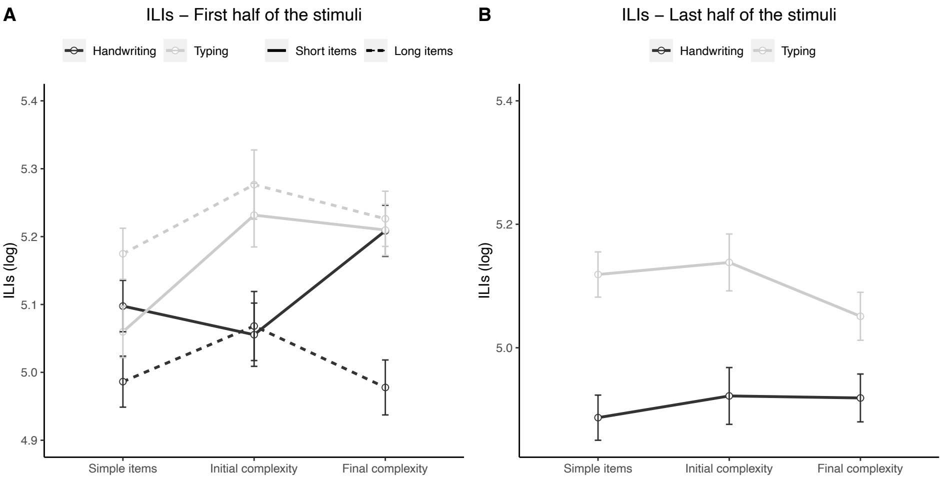
Splitting the initial and final ILIs

In this section, we want to make a step further in analyzing the effect of Complexity position on ILIs, the execution measures that gave more intriguing results on handwriting and typing differences. The position of the complexity seemed to be processed sequentially during handwriting, i.e., an initial complexity affected RTs, then a final complexity affected ILIs. In typing, an initial complexity strongly affected RTs and ILIs, while a final complexity showed no effect on letter intervals. To identify the possible locus of final complexity processing, we analyzed separately the mean ILIs in the first and in the last half of the letters composing a stimulus. For stimuli with an odd number of ILIs, we did not consider the ILI in the middle, i.e., for the stimuli with 4 and 8 letters (see the same procedure in Scaltritti et al., 2016). We added a constant (= 9 ms) to all ILIs to avoid 0 value (i.e., when a handwriting ILI had 0 value, see Statistical Analysis). This allowed computing the logarithm of the dependent variables. Models' construction, selection and reporting procedure were the same as described for the precedent ILI analysis. For the complete models, see Supplementary Materials, Table B.

First half ILIs. The effect of Complexity Position was significant (F = 11.95, $p < .001$) as well as its interaction with Length (F = 5.80, $p = .004$) and with Task (F = 11.33, $p < .001$). These interactions were qualified by a higher-order interaction between Complexity Position, Length, and Task (F = 8.19, $p < .001$). Contrasts showed that, in typing short stimuli, both the complexity at the initial and final positions elicited slower ILIs in the first half of the stimulus ($t_{\textit{simple short – initial short}} = –4.64$, $p < .001$, $t_{\textit{simple short – final short}} = –5.46$, $p < .001$). For long stimuli, the trend looked similar, even if not significant ($t_{\textit{simple short – initial short}} = –2.55$, $p = .117$, $t_{\textit{simple short – final short}} = –1.86$, $p = .430$). In handwriting short stimuli, only a final complexity slowed down initial ILIs ($t_{\textit{simple short – initial short}} = .88$, $p = .950$, $t_{\textit{simple short – final short}} = –4.17$, $p < .001$). The pattern for long stimuli looked opposite, even if not significant ($t_{\textit{simple short – initial short}} = –2.06$, $p = .312$, $t_{\textit{simple short – final short}} = .28$, $p = 1.000$). Figure 5, panel A shows a graphical representation of the higher-order interaction.

Last half ILIs. The two writing modalities showed different trends in dealing with the complexity during the last half of the stimulus, as attested by the significant interaction between Complexity Position and Task (F = 11.70, p < .001), the unique interaction retained in the model. In typing, a complexity in final position significantly accelerated the final movements ($t_{\textit{simple – initial}} = –.60$, $p = .823$, $t_{\textit{simple – final}} = 2.62$, $p = .026$), while in handwriting the ILIs reached a stable velocity independently from the complexity ($t_{\textit{simple – initial}} = –.1.16$, $p = .568$, $t_{\textit{simple – final}} = –1.22$, $p = .445$). Figure 5, panel B shows a graphical representation of the interaction.

Figure 5. Graphical representation of the significant higher-order interactions in initial (panel A) and final ILI (panle B) analyses on Complexity Position



Note. Panel A shows the log-transformed ILIs of the first half of the stimuli for the interaction between Complexity Position, Length and Task. Panel B shows the log-transformed ILIs of the last half of the stimuli for the interaction between Complexity Position and Task. Error bars show standard errors.

Discussion

The main aim of this study was to compare handwriting and typing in terms of the interaction between linguistic-central processes and peripheral-motor processes in the two written production modalities. Participants typed and handwrote a set of Italian stimuli in which lexicality (words and pseudowords), orthographic complexity (simple and complex stimuli), and length (short and long stimuli) were manipulated. In both tasks, latency (RTs) and the difference between RTs and acoustic duration (RT–AD) were measured, and assumed to index the scope of initial planning (i.e., central processes loading before handwriting/typing initiation). To detect possible linguistic effects during handwriting/typing execution, the mean length of interletter intervals (ILIs), assumed to index local planning and execution of the linguistic units, and whole response duration (WRD), assumed to index the cumulative effects of the factors involved, were also recorded.

Overall, the linguistic variables showed an effect on both typing and handwriting. However, they impacted the two production modalities differently, casting light on fundamental processing modes. For handwriting, the pattern of results was compatible with a cascaded flow of linguistic processing during written execution, while for typing a more intertwined pattern of cascade and serial processing emerged. In the following sections we discuss the effects distinguishing handwriting and typing production before (RTs and RT–AD) and during (ILIs and WRD) their execution.

Central processing before peripheral processes: RTs and RT–AD

Lexicality affected RTs in both handwriting and typing, with shorter latencies to start real words compared to pseudowords. This result is consistent with reports for both typing (see e.g., Baus et al., 2013; Bloemsaat et al., 2003; Pinet et al., 2016; Scaltritti et al., 2016) and handwriting (e.g., Delattre et al., 2006; Kandel & Perret, 2015; Lambert et al., 2008; Roux et al., 2013), and it is usually interpreted as being due to a fast retrieval of words from the lexicon and a slow, sequential spell out of pseudowords. Consistent with this account, the effect of lexicality was modulated by length as the latter affected only pseudowords, that is, longer pseudowords required longer RTs than shorter stimuli.

The effect of lexicality on RTs was stronger in typing. This result is corroborated analyzing latency against the acoustic duration of the stimuli (RT–AD), where the lexicality effect emerged only in typing long stimuli, these being the items imposing the heaviest weight on processing. Specifically, participants started typing long stimuli before the offset of the acoustic signal, except when they were typing long pseudowords, for which the production started after the acoustic offset of the stimuli. Interestingly, in handwriting, both long pseudowords and long words were started before hearing the entire stimulus. This pattern observed for handwriting is consistent with the view of a continuous flow from central to peripheral processes in an interactive-activation mode (Roux et al., 2013), in which not all lexical and letter information is necessarily accessed and activated before starting to write. The distinct patterns observed in the two production modalities could be ascribed to a major effort in processing the orthographic representation and in preparing the corresponding motor response in typing compared with handwriting. In line with serial models, RTs in typing could reflect fully pre-processed lexical information, and also constituent parallel (i.e., simultaneous) keystrokes' activation (Crump & Logan, 2010). However, a cascaded processing is not excluded for both production modalities, given that lexicality affected also response execution. More details on this issue are in the below section, dedicated to ILIs and WRD.

In the main analysis, latency and RT–AD were not affected by the presence of an orthographic complexity in either production modality, indicating that the complexity was not resolved before execution. A more complicated picture emerged when we analyzed latency with respect to the position of the complex grapheme within the string. When the complex grapheme was at the initial position, RTs had a delay compared to simple stimuli, while no effect arose when the complex grapheme was in the final position. This suggests that, in handwriting and typing to dictation, at least a few phonemes are analyzed before starting. The lag between the initial phonemes' processing and the actual writing/typing enables to detect and process the complexity in the initial position. A number of alternative choices for the correct phoneme-to-grapheme mapping are generated, and such an operation causes a delay. Since no effect was found for complex graphemes in the final position, we may confirm the hypothesis that planning of the string does not involve the entire string, that is, the linguistic processing is not completed before peripheral processes start. Looking at the RT–AD in handwriting, this measure was not affected by the position of the complexity. The decision to start writing a complexity is not dependent on the length of the acoustic signal. In typing, the same was true for short stimuli, but the presence of a final complexity sped up long stimuli, which tended to start before the end of the acoustic stimulus. We propose that in typing, the initial motor programming starts after the access to a larger portion of the orthographic representation than the one required in handwriting. Indeed, while handwriting of long stimuli starts before hearing the entire acoustic signal, in typing there is a tendency to start most stimuli after the end of the acoustic signal, and systematically later than in handwriting. The anticipation found in initiating the long stimuli with a final complexity might be due to the salience of a final complex phoneme, such as [ɲ], [ʃ], [ʎ], [k], [g], [kw] (corresponding to the complex grapheme *gn*, *sc*, *gl*, *ch*, *gh*, *qu*), which might allow the item to be identified, and to discard possible lexical candidates (i.e., the uniqueness point; see e.g., Marslen-Wilson, 1987; Radeau et al., 1989).

Central processing during peripheral processes: ILIs and WRD

All the considered linguistic variables affected written execution but interacted differently with the task modality. The main differences between typing and handwriting ILIs and WRD emerged in inspecting the interactions of length with the other linguistic variables. Regarding ILIs, in typing, the length effect was present in pseudowords, and in both complex and simple stimuli; in handwriting, the effect of length was absent or even opposite in complex stimuli and in pseudowords. Regarding WRD, long items took a clearly longer production time compared to short items in both task modalities. However, the effect was stronger in typing. According to a linguistic point of view, the length effect reflects the "syllable effect" (i.e., longer ILIs at syllable boundaries) found in typing (Weingarten at al. 2004) and in handwriting (Álvarez et al., 2009; Kandel et al., 2006; Kandel & Valdois, 2006; Lambert et al., 2008). However, we did not find such an effect in handwriting ILIs; rather, we found the opposite effect in pseudowords and in complex stimuli. Thus, handwriting seems to accelerate interletter selection when processing a stimulus that requires a stronger memory load. As far as we know, a similar finding has not been documented in the handwriting literature, probably because ILIs are usually inspected individually and not mean aggregated. We interpreted this result in line with findings on peripheral-motor dynamics, which documented that velocity in handwriting is affected by proportional changes depending on the linear extension of the to-be-written strings (i.e., different sizes of a word; see e.g., Lacquaniti et al., 1983). Here, we showed an acceleration of the pen lifts within letters in long items, as a function of their linguistic features: complexity and lexicality. Conversely, typing long items requires heavier interletter selection processing, which seems to depend mostly on length than on other linguistic variables. Studies on motor planning in typing showed longer interkeystroke intervals in the middle of typed long items (around the 4th letter; Larochelle, 1983; Ostry, 1983). Therefore, the longer ILIs we found in long items could be due not only to the selection of syllables but also to a limited capacity of the motor buffer that has to be reloaded after processing a three-to-five letter segment, not necessarily compatible with a single syllable. The typing pattern may reflect constraints imposed by the peripheral mechanisms involved in the motor planning system. The interactions of length with the other linguistic variables are helpful in building a thorough picture of the differences between typing and handwriting.

Looking at lexicality and its interaction with length in handwriting, ILIs were longer for pseudowords than for words, irrespective of length, while in typing the same was true for long stimuli but there was no difference for short stimuli. This pattern is incompatible with the view that the planning is completed before starting the written execution movements, as, in this case, we should not expect differences between words and pseudowords. Moreover, it rules out the simplistic view that in both production modalities only a first portion of the stimulus is planned in advance, as, in this case, we should expect differences between either long or short words and pseudowords. Such a difference was found in handwriting, confirming our expectation for online processing of lexicality irrespective of length. However, the fact that short items were not affected by lexicality in typing signals a difference in planning between the two production modalities. This pattern may be accounted for by assuming that short stimuli were completely processed in advance in typing and therefore the typing process for such items is a read-out process from a temporary memory buffer. The stronger lexicality effect before typing production (i.e., in RTs and RT–AD) corroborates this view.

WRD analysis added evidence in favor of a differential planning between handwriting and typing. In both modalities, there was no difference in WRD between short words and pseudowords; for long items, pseudowords were overall typed more slowly than words, but no lexicality effect was found in handwriting. Such a pattern in typing confirmed a possible rehearsal of linguistic information only for long pseudowords. Jointly considered with ILIs, the WRD results in handwriting ruled out a sharp distinction between planning and execution, as well as a view of planning being a simple function of the length of the material to be planned. Given that handwriting WRD includes execution of letters, while ILIs reflect the pause between letters, the lack of a lexicality effect on WRD in handwriting suggested that any possible initial advantage of words over pseudowords was absorbed into the letter writing process (rather than added to it) as time increased.

Considering orthographic complexity and its interaction with length, in the main analysis, the presence of an orthographic complexity –compared to simple stimuli– did not affect ILIs in typing, while in handwriting ILIs were significantly slower for complex than for simple stimuli, irrespective of length. The latter finding is in line with expectations and previous results (e.g., Kandel et al., 2013), but the absence of the effect in typing is intriguing and poses the basis of the fine-graded explorative analysis on the complexity position which underlined interesting differences between handwriting and typing. For handwriting, only the final complexity affected ILIs, while the initial complexity did not, being processed before its production and consequently affecting RTs. The additional analyses on the initial and final half of the strings gave insights on the probable locus of the complexity processing, showing that ILIs were slower at the beginning of short stimuli with a final complexity. This finding is compatible with a cascaded view during handwriting, which suggests that the complexity is processed immediately before its production, showing effects during the execution of the previous syllable (Kandel et al. 2011). Consistent with this explanation, ILIs in the first half of long stimuli with a final complexity and simple stimuli did not differ: the complexity was processed later on, during the last half of the strings, even if we found only numerically slower final ILIs for such long complex stimuli in comparison to simple ones.

For typing, the effect of the initial complexity was present on RTs as in handwriting, but it percolated on ILIs which were higher in the first half of the strings as compared to strings without complexities, especially when the strings were short. The presence of a final complexity slowed down ILIs on the first half of the strings similarly, even if less strongly, to an initial complexity, proving that its processing was carried out in parallel with the motor execution. This pattern is clearly inconsistent with a serial model that does not predict an effect on execution. Previous electrophysiological studies, taking advantage of motor evoked potentials (MEPs), showed that, at the onset of typing, motor information on hand alternation is detected only for the first part of the string (Behmer et al., 2018; Scaltritti et al., 2018). In line with serial models, Behmer et al. (2018) proposed that all keystroke identities are processed and activated in parallel before typing execution. Later, during execution, the actual keystrokes inhibited the following ones according to a graduated activation. Scaltritti et al. (2018) questioned the assumption that all keystroke identities are programmed before typing, assuming that the identity of the keystrokes placed after the third letter could be planned later, during motor execution. In line with an ongoing linguistic planning during production, our findings showed that keystroke programming was affected not only by motor constraints (such as hand/finger identity), but also by linguistic information related to orthographic complexity that slowed down the execution of the segment preceding the complexity (i.e., slower RTs before initial complexity and slower first half ILIs before a final complexity). Furthermore, the actual execution of a complex segment located at the beginning of the strings could have caused a deceleration in processing the last part of those strings, consequently slowing down the initial complex keypresses. An acceleration was detected during the execution of the last half of the stimuli with final complexity, suggesting again that the last segment was programmed beforehand.

Finally, orthographic complexity had a negligible general effect on WRD, even if both the main analysis and the explorative analysis on the complexity position confirmed a three-way interaction between complexity, length and task. In typing results were similar to those described for ILIs, but in handwriting the final complexities tended to accelerate WRD, especially for short stimuli, while slowing down ILIs. Overall, in terms of the dual-route model of spelling (Barry, 1994), our data suggested that in handwriting the inconsistency between the outputs of the lexical and the sublexical routes caused by the presence of an orthographic complexity affected ILIs, but it did not propagate to WRD. One possible explanation is that the effect of orthographic complexity was "absorbed" in WRD, which included both ILI and letter production, due to motor-related factors (e.g., length, number of strokes) or by the fluctuation of timing during writing (e.g., acceleration of long words). Another explanation relates to the fact that the decision about which letter to execute next and the actual execution were interrelated in such a way that a longer ILI allowed for better targeting of the letter and this may allow for a more direct and shorter execution movement. It could be the case that the letters comprising complex graphemes are chunked in one unit, and the spelling program associated with the grapheme reflects this unity rather than the composing letters (see also Houghton & Zorzi, 2003). Indeed, most of the irregularities we considered are the recurring combination of two graphemes (a digraph) that correspond to a single phoneme (e.g., *gn* - [ɲ]; *sc* - [ʃ]; *gl* - [ʎ]; *ch* - [k]; *gh* - [g], but also *qu* - [kw] which always occurred together). While this account is viable, and although it has been invoked in a different form for handwriting English geminates (Kandel et al., 2013, but see also Kandel et al., 2019), the specific dynamics of ILIs and single letter/digraph durations have not yet been made clear.

Conclusions

As the main contribution of our work, we shed light on how linguistic processing affects handwriting and typing differently. We conclude that typing and handwriting sensory-motor peculiarities cause a different processing flow of linguistic variables during execution. While for handwriting we confirmed a cascade processing of lexical and sublexical variables, typing was characterized by an interplay between cascade and serial planning. This pattern indicates modality-specific, time-locked planning and execution strategies in dealing with linguistic information. There is an interplay between the initial construction of the orthographic representation, but the differences between typing and handwriting in programming and producing a letter sequence, both in time and in gestures, inevitably affect working memory capacity, associated attentional resources, and therefore the extent of cascade planning. We propose the interaction of peripheral processes and the graphemic buffer (the memory storage of the orthographic representation) as the locus of the differences between typing and handwriting.

Both typing and handwriting are still under-investigated compared to other forms of linguistic production. With this study, we aimed to add insights into the interaction between linguistic and sensory-motor processes to make a step towards more detailed models of written production.

Limitations

One limitation regards the difficulty in choosing execution measures to directly compare typing and handwriting. As was mentioned in the introduction, while in handwriting ILIs correspond to pen lifts between letters, in typing the execution of the letter (the keypress) is included. More specifically, in handwriting, an ILI starts when the pen is lifted (from the last pen press) and finishes at the first pen press of a new letter. In typing, an ILI starts from a keypress, which is a letter execution planned in the previous ILIs, and finishes on another keypress (that does not comprise a key release, so it is not properly an execution). This difference may prevent considering ILIs as equal between the two tasks. However, we interpreted ILIs as a measure of interletter interval (i.e., selection), exactly as they have been largely used in previous literature. Finding a measure of pure letter execution in typing, such as keypress duration, or considering a pen lift together with the preceding letter execution in handwriting, might be the goals for future exploration to understand the fine-grade mechanics of the interaction of motor and linguistic processes.

Another methodological limitation concerns the use of two different software tools for measuring typing and handwriting. Despite recent huge improvements in perfecting handwriting tools for data collection and analysis, they lack all the potentialities of more common tools for keypress collection. In addition, while typing measures can be automatically extracted, for handwriting a large part of the work in the segmentation of words and/or letters is still on the hand of the analyst, and so more subject to error. For this reason, we double-checked the ILIs extraction, reporting the inter-rater reliability (see Statistical analysis section).

Finally, our stimuli were created and controlled with the aim to examine complexity effects per se. Therefore, they lack a fine-graded balance of the complexity position. We plan future research to investigate in more depth the effect of this variable.

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References

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/https://doi.org/10.3758/s13421-014-0489-8

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

Angelelli, P., Notarnicola, A., Costabile, D., Marinelli, V., Judica, A., Zoccolotti, P., & Luzzatti, C.

(2008). *DDO. Diagnosi dei disturbi ortografici in età evolutiva.* Edizioni Erickson.

Audacity Team. (2019). *Audacity(R): Free Audio Editor and Recorder [Computer application]. Version 2.3.3*. https://audacityteam.org/.

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

Bates, D. M., Kliegl, R., Vasishth, S., & Baayen, H. (2015). Parsimonious mixed models Douglas Bates. *ArXiv Preprint ArXiv:1506.04967*.

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

Behmer, L., J., J. K., Martinez, S., Walls, R., Amir-Brownstein, E., Jaye, A., Leytze, M., Lucier, K., & Crump, M. J. C. (2018). Parallel regulation of past, present, and future actions during sequencing. *Journal of Experimental Psychology. Human Perception and Performance*, *44*(8), 1147–1152. https://doi.org/10.1037/XHP0000507

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*, *67*(2), 123–133. https://doi.org/10.1007/s00426-002-0112-7

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

Cerni, T., Longcamp, M., & Job, R. (2016). 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. (2016). 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

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. (2003). Articulatory Duration in Single-Word Speech Production. *Journal of Experimental Psychology: Learning Memory and Cognition*, *29*(3), 416–431. https://doi.org/10.1037/0278-7393.29.3.416

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

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

Fox, J., & Weisberg, S. (2019). *An R Companion to Applied Regression, 3rd Edition*. Thousand Oaks, CA.

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

Goslin, J., Galluzzi, C., & Romani, C. (2014). PhonItalia: A phonological lexicon for Italian. *Behavior Research Methods*, *46*(3), 872–886. https://doi.org/10.3758/s13428-013-0400-8

Grudin, J. T., & LaRochelle, S. (1982). Digraph frequency effects in skilled typing. In *(CHIP rep.110). La Jolla, CA: University of California, San Diego, Center for Human Information Processing* .

Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology*, *20*(2), 115–162.

https://doi.org/10.1080/02643290242000871

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., 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., Ghimenton, A., & Perret, C. (2019). Letter coding affects movement production in word writing: an English–Italian cross-linguistic study. *Reading and Writing*, *32*, 95–114. https://doi.org/https://doi.org/10.1007/s11145-017-9756-y

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

Kello, C. T., Plaut, D. C., & MacWhinney, B. (2000). The task dependence of staged versus cascaded processing: An empirical and computational study of stroop interference in speech production. *Journal of Experimental Psychology: General*, *129*(3), 340–360. https://doi.org/10.1037/0096-3445.129.3.340

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

Lacquaniti, F., Carlo, T., & Viviani, P. (1983). The law relating the kinematic and figural aspects of drawing movements. *Acta Psychologica*, *54*(1–3), 115–130. https://doi.org/https://doi.org/10.1016/0001-6918(83)90027-6

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 *Cognitive Aspects of Skilled Typewriting* (pp. 67–94). https://doi.org/10.1007/978-1-4612-5470-6_4

Lenth, R., Singmann, H., Love, J., Buerkner, P., & Herve, M. (2019). emmeans: Estimated Marginal Means, aka Least-Squares Means. In *R package version 1.3.2*. https://doi.org/10.1080/00031305.1980.10483031>.License

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. In B. H. Ross (Ed.), *Psychology of Learning and Motivation - Advances in Research and Theory* (p. Vol. 54, pp. 2–19). Accademic Press. 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

Marinelli, C. V., Angelelli, P., Notarnicola, A., & Luzzatti, C. (2009). Do Italian dyslexic children use the lexical reading route efficiently? An orthographic judgment task. *Reading and Writing*, *22*(3), 333–351. https://doi.org/10.1007/s11145-008-9118-x

Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word-recognition. *Cognition*, *25*(1–2), 71–102. https://doi.org/10.1016/0010-0277(87)90005-9

Massaro, D. W., & Lucas, P. A. (1984). Typing letter strings varying in orthographic structure. *Acta Psychologica*, *57*(2), 109–131. https://doi.org/10.1016/0001-6918(84)90038-6

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

Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., & Bates, D. (2017). Balancing Type I error and power in linear mixed models. *Journal of Memory and Language*, *94*, 305–315. https://doi.org/10.1016/j.jml.2017.01.001

Nottbusch, G., Grimm, A., Weingarten, R., & Will, U. (2005). Syllabic sructures in typing: Evidence from deaf writers. *Reading and Writing*, *18*, 497–526. https://doi.org/10.1007/s11145-005-3178-y

Ostry, D. J. (1983). Determinants of Interkey Times in Typing. In W. E. Cooper (Ed.), *Cognitive Aspects of Skilled Typewriting* (pp. 225–246). Ney York: Springer-Verlag. https://doi.org/10.1007/978-1-4612-5470-6_9

Palmis, S., Velay, J. L., Fabiani, E., Nazarian, B., Anton, J. L., Habib, M., Kandel, S., & Longcamp, M. (2019). The impact of spelling regularity on handwriting production: A coupled fMRI and kinematics study. *Cortex*, *113*, 111–127. https://doi.org/10.1016/j.cortex.2018.11.024

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

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

Purcell, J. J., Turkeltaub, P. E., Eden, G. F., & Rapp, B. (2011). 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/

Radeau, M., Mousty, P., & Bertelson, P. (1989). The effect of the uniqueness point in spoken-word recognition. *Psychological Research 1989 51:3*, *51*(3), 123–128. https://doi.org/10.1007/BF00309307

Rapcsak, S. Z., & Beeson, P. M. (2002). Neuroanatomical correlates of spelling and writing. In A. E. Hillis (Ed.), *Handbook of Adult Language Disorders: Integrating Cognitive Neuropsychology, Neurology, and Rehabilitation* (pp. 71–99). Psychology Press.

Rapp, B., & Caramazza, A. (1997). From Graphemes to Abstract Letter Shapes: Levels of Representation in Written Spelling. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(4), 1130. https://doi.org/10.1037/0096-1523.23.4.1130

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

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

Scaltritti, M., Alario, F. X., & Longcamp, M. (2018). The Scope of Planning Serial Actions during Typing. *Journal of Cognitive Neuroscience*, *30*(11), 1620–1629. https://doi.org/10.1162/JOCN_A_01305

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

Seidenberg, M. S., & McClelland, J. L. (1989). A Distributed, Developmental Model of Word Recognition and Naming. *Psychological Review*, *96*(4), 523–568. https://doi.org/10.1037/0033-295X.96.4.523

Sternberg, S., Knoll, R. L., & Wright, C. E. (1978). Experiments on temporal aspects of keyboard entry. In J. P. Duncanson (Ed.), *Gelling it together: Research and applications in human factors* (pp. 28–50). Santa Monica, CA: Human Factors Society. https://doi.org/10.1016/0003-6870(79)90220-5

Teulings, H. L., Thomassen, A. J. W. M., & Van Galen, G. P. (1983). Preparation of partly precued handwriting movements: The size of movement units in handwriting. *Acta Psychologica*, *54*, 165–177. https://doi.org/10.1016/0001-6918(83)90031-8

Van Galen, G. P. (1990). Phonological and motoric demands in handwriting: Evidence for discrete transmission of information. *Acta Psychologica*, *74*, 259–275.

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 Galen, G. P., Smyth, M. M., Merlenbroek, R. G. J., & Hylkema, H. (1989). The role of short-term memory and the motor buffer in handwriting under visual and non-visual guidance. In R. Plamondon, C. Y. Suen, & M. L. Simner (Eds.), *Computer Recognition and Human Production of Handwriting* (pp. 253–271). World Scientific Pub. Sngapore. https://doi.org/10.1142/9789814434195_0018

Van Selst, M., & Jolicoeur, P. (1994). A Solution to the Effect of Sample Size on Outlier Elimination. *The Quarterly Journal of Experimental Psychology Section A*, *47*(3), 631–650. https://doi.org/10.1080/14640749408401131

Weingarten, R., Nottbusch, G., & Will, U. (2004). Morphemes, syllables, and graphemes in written word production. In T. Pechmann & C. Habel (Eds.), *Multidisciplinary approaches to speech production* (pp. 529–572). Berlin: Mouton de Gruyter.

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

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York.

Wu, C., & Liu, Y. (2008). Queuing network modeling of transcription typing. *ACM Transactions on Computer-Human Interaction*, *15*(6). https://doi.org/10.1145/1352782.1352788