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The impact of orthographic complexity on handwriting and typing in a shallow orthography

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Abstract

Handwriting and typing involve distinct motor processes that influence how orthographic information is managed during word production. This study investigated how orthographic complexity—specifically digraphs—affects writing execution in Italian, a shallow orthography, in both adults (N=36, M_{age} = 23.58) and adolescents (N=36, M_{age} = 14.75). Participants completed a dictation task involving 32 stimuli (words and pseudowords) containing a digraph, writing them in both handwriting and typing modalities. During writing, interletter intervals (ILIs) were measured at three critical points: before the digraph (Syllable-Boundary-ILI), within the digraph (Digraph-ILI), and after the digraph (Post-Digraph-ILI). Results showed that across modalities and age groups, the Syllable-Boundary-ILI was longer than the other ILIs, indicating pre-planning of the following orthographic sequence. In handwriting, ILIs progressively shortened across the three positions, whereas in typing, ILIs remained constant within and after the digraph. Adolescents exhibited greater difficulty in initiating the digraphs and the subsequent vowels, particularly in typing, the modality they were less experienced with. These findings suggest that handwriting supports more cohesive motor planning of orthographic units, while typing relies on a more discrete approach, especially in younger, less skilled writers.

Keywords Orthographic complexity · Handwriting · Typing · Motor planning · Spelling · Writing development

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Introduction

Handwriting and typing are two distinct modalities of written production that rely on common high-level linguistic processes, such as lexical and sublexical mechanisms, but differ in their low-level sensorimotor demands (Purcell et al., 2011). These motor processes, often referred to as peripheral processes, are specific to the modality used. Handwriting involves the precise formation of letter shapes through hand movements, whereas typing requires accurate key presses based on pre-learned motor patterns in skilled typists or visual guidance in less experienced individuals (e.g., Cerni & Job, 2022; Mangen & Velay, 2010; Spilling et al., 2023). These fundamental differences in physical and cognitive demands not only impact writing speed but also critically influence how central linguistic processes interact with motor execution (Cerni & Job, 2022, 2023). This study aimed to explore the similarities and differences between these two writing modalities, focusing on the processing and execution of digraphs —two-letter clusters that correspond to single phonemes— in a shallow orthography like Italian, by examining the temporal execution of these orthographically complex graphemes.

Research at the intersection of psycholinguistics and writing movement analysis has shown that motor execution is shaped by ongoing linguistic processing (Afonso & Álvarez, 2019; Kandel, 2023). In handwriting, temporal measures such as letter durations, inter-letter intervals, and whole-word writing times are modulated by lexical and sublexical variables, including grapheme-phoneme consistency, word frequency, and syllabic structure. These effects emerged in both deep orthographies (Danna et al., 2022; Delattre et al., 2006; Kandel & Spinelli, 2010; Kandel & Valdois, 2006; Kandel et al., 2006a, 2006b, 2013; Lambert et al., 2011; Palmis et al., 2019; Planton et al., 2019; Roux et al., 2013) and shallow orthographies, though the latter was studied less extensively (e.g., Afonso et al., 2015, 2018; Álvarez et al., 2009). Similarly, in typing, inter-key intervals —the time between consecutive key presses— reflect ongoing spelling processes during execution with evidence emerging from studies on deep orthographies (Bloemsaat et al., 2003; Pinet et al., 2016, 2022) and shallow orthographies (Cerni et al., 2016a, 2016b; Rønneberg & Torrance, 2019; Sahel et al., 2008; Scaltritti et al., 2016; Weingarten et al., 2004).

Orthographic complexity, a key variable in studies on linguistic influence during writing motor execution, refers to the challenges writers face in spelling words which often stem from deviations from straightforward phoneme-grapheme correspondences. Irregular phoneme-grapheme correspondences were shown to significantly impact handwriting by increasing whole-word durations (Delattre et al., 2006), alternating single-letter durations (Afonso et al., 2015; Kandel et al., 2013; Roux et al., 2013), and inter-letter intervals (Afonso et al., 2015; Kandel et al., 2013). In typing, the influence of orthographic complexity on execution was evidenced in studies that reported altered inter-key intervals and longer reaction times when executing words containing complex graphemes (Bloemsaat et al., 2003; Pinet et al., 2016; Rønneberg & Torrance, 2019).

In shallow orthographies like Italian, phoneme-to grapheme mappings are generally regular and predictable, leading to lower orthographic complexity (e.g., Arfé et al., 2019). However, certain words pose challenges to spelling due to context-sensitive orthographic rules (Arfé et al., 2018; Barca et al., 2007; Burani et al., 2006; Notarnicola et al., 2012). In reference to sound-to-spelling complexity, certain sounds are transcribed as two-letters graphemes, i.e., digraphs. In detail, <ch> represents the sound /k/ when followed by *i* or *e* (*chiesa* [church]), <sc> denotes /ʃ/ before *i/e* (*sci* [ski]), <gl> corresponds to /ʎ/ before *i* (*famiglia* [family]), and <gn> signals /ɲ/ (*bagno* [bathroom]), independently from the subsequent vowel. Digraphs add complexity to spelling processing, as they introduce a potential conflict between distinct representational levels of the orthographic structure: one for grapheme units, which provide an abstract representation of phonemes, and another for letter units, as proposed by connectionist models (Houghton & Zorzi, 2003) and evidenced in spelling (Tainturier & Rapp, 2004) and handwriting analyses (Kandel et al., 2006a, 2006b).

Fine-grained analyses of handwriting demonstrated that complex graphemes composed of more than one letter affect single letter duration. For instance, Kandel and Spinelli (2010) showed that, in French, letter duration depended on grapheme length: one-letter graphemes had shorter durations than the initial letter of digraphs or three-letter graphemes. Similarly, Spinelli et al., (2012) observed that the presence of strongly cohesive digraph (consistently corresponding to a single phoneme) required more programming effort, as evidenced by slower letter durations preceding the grapheme, compared to weakly cohesive ones (representing a single phoneme or decomposable into two). Additionally, Kandel et al., (2013), exploring the execution of doublets in English, found that their presence affected both letter and interletter interval duration, leading to a slowing down before and during the grapheme execution compared to when doublets were absent. Together, these findings suggests that complex graphemes are processed as clusters.

Despite existing typing research, the specific time intervals associated with typing complex graphemes have remained unexplored. Studies investigating orthographic complexity focused on the word (e.g.., Rønneberg & Torrance, 2019) and syllable (Pinet et al., 2016) levels, calculating mean interkeystroke durations, yet findings were inconsistent. Similarly, in the context of handwriting in shallow orthographies like Italian, the temporal dynamics of producing complex graphemes have not been thoroughly examined. Thus, limited information is available on possible different processing of complex graphemes due to writing modality constraints. To contribute to filling this gap, the present study aimed to compare handwriting and typing by analyzing the duration of specific intervals within complex graphemes in a shallow orthography like Italian. We extended two prior studies by Cerni and Job (2022, 2023) that compared linguistic processing during handwriting and typing, focusing —though not exclusively— on orthographic complexities such as Italian digraphs and transcription ambiguities. Specifically, Cerni and Job (2022) suggested that processing complex orthographic units is more anticipatory at the whole-word level in typing, influencing the initial execution of the word, compared to handwriting, where the effect is more evident in the ongoing execution. This difference was observed in adults with consolidated handwriting and typing experience. Building on this, Cerni and Job (2023) explored these effects in 9th-grade adolescents with well-established handwriting skills but less proficiency in typing. Interestingly, the effect of orthographic complexity was more pronounced in this younger group when typing, suggesting that lower automatization of this writing modality amplifies the influence of orthographic complexity. These findings highlighted how experience and modality-specific motor planning shape the temporal dynamics of writing. However, these studies primarily analyzed word-level temporal variables, such as mean interletter intervals and whole-word durations, examined a broader range of orthographic complexities, and did not compare directly adults and adolescents. Therefore, we revisited the data from these two studies, focusing specifically on stimuli presenting digraphs and extracting temporal interval durations between the letters involved in their execution.

The study sought to explore the following research questions (RQ): how Italian digraphs influence motor execution according to (RQ1) modality-specific demands, comparing handwriting and typing, and (RQ2) varying levels of expertise with the writing modalities, comparing adults and adolescents.

Participants wrote stimuli on a digitizing tablet to capture InterLetter Intervals (ILIs) —the time elapsed between two pen lift between consecutive letters—, and typed the same stimuli on a standard keyboard, with timing data recorded for keypress intervals —the time elapsed between two consecutive keypresses—, here commonly referred as ILIs. We extracted ILIs, considering this a comparable measure across both writing modalities, as it was previously used in both typing and handwriting literature to reflect processing involved in interletter selection. While other measures related to letter execution, especially in handwriting, could be considered, we did not include them in this study, as they could not be isolated, especially in in typing, with the available apparatus (see Limitations for further discussion).

Stimuli consisted in a set of Italian words and pseudowords containing a digraph (i.e., *ch*, *sc*, *gl*, *gn*, followed by vowels that adhere to context-dependent rules, as described earlier as well as in Materials and Method). Each digraph corresponded to the initial letter of the stimulus's final syllable, thus the first letter of the digraph consistently followed a syllable boundary, a position that aligns with the structural and phonological constraints of Italian, where such digraphs naturally occur. We assessed ILIs at three key positions within the stimuli: first, the interval between the letter immediately preceding the orthographic digraph and the initial letter of the digraph (corresponding to a syllable boundary, Syllable-Boundary-ILI); second, the interval separating the two letters constituting the digraph (Digraph-ILI); and third, the interval between the final letter of the digraph and the vowel that follows it (Post-Digraph-ILI). For example, in the word *sogni* (dreams), where the digraph <gn> represents the orthographic complexity, the Syllable-Boundary-ILI captured the interval between *o* and *g*, the Digraph-ILI measured the interval between *g* and *n*, and the Post-Digraph-ILI corresponded to the interval between *n* and *i*.

To investigate the potential differences in planning and execution of digraphs across handwriting and typing (RQ1), we compared ILIs at various positions within syllables, including a comparison between words and pseudowords to examine lexical and sublexical effects. Additionally, to explore how experience influences the execution of complex orthographic elements (RQ2), we compared ILIs between adults with extensive handwriting and typing experience and 9th-grade adolescents who were well trained in handwriting for academic purposes but had less automatized typing skills, despite both modalities exhibited slower execution than adults. We hypothesized that variations in ILI patterns would arise due to the anticipatory processing of upcoming letters and the hierarchical organization of orthographic representations, which could differ based on modality constraints as well as varying levels of automatization in linguistic-motor integration between the groups. As we analyzed ILIs, we focused our hypotheses on the processing involved in interletter selection.

Specifically, with respect to RQ1, we expected the Syllable-Boundary-ILI to be longer than the other ILIs, in accordance with previous studies that found longer intervals at syllable boundaries in both handwriting (Kandel & Valdois, 2006; Kandel et al., 2006a, 2006b, 2011; Lambert et al., 2008) and typing (Nottbusch et al., 2005; Pinet et al., 2016; Weingarten et al., 2004), suggesting that the processing of upcoming letters is anticipated before the syllable execution starts. According to the APOMI (Anticipatory Processing of Orthographic and Motor Information) model proposed by Kandel (2023), linguistic processing occurs in parallel with motor execution, allowing for online segmentation of orthographic representations into hierarchical units, such as syllables and graphemes. These units are processed anticipatorily and accessed in a continuous top-down flow from orthographic to motor processes. In line with this dynamic processing, the Digraph-ILI would be preplanned during the preceding ILI, making it shorter than the previous interval. For the Post-Digraph-ILI, we expected either an acceleration or deceleration in respect to the Digraph-ILI, depending on whether the digraph and following vowels were pre-processed as a cohesive orthographic unit or as separate graphemic components. Furthermore, by examining ILIs at different positions within the syllable based on the lexicality, we expected shorter processing times for the syllable (Syllable-Boundary-ILI) in words than in pseudowords, as lexical access would speed up the processing of the orthographic units (Roux et al., 2013). We also explored potential acceleration of the vowel following the digraphs based on lexical access, as well as on written modality used.

With respect to RQ2, we predicted differences between the two age groups, particularly regarding typing, as this modality had a more unbalanced experience between the groups. Specifically, we expected greater variability across different types of ILIs in adolescents compared to adults, i.e., slower execution times for the Post-Digraph-ILI compared to the Digraph-ILI in adolescents than in adults. This may be attributed to less automatization in their typing skills, which might result in different mechanisms for processing orthographic units compared to adults, possibly due to memory constraints in maintaining the orthographic sequence while executing less skilled motor pattern. We did not rule out the possibility of group differences in handwriting, as adolescents showed slower execution than adults. However, because handwriting was extensively trained, we expected these differences to be negligible.

By examining the temporal dynamics of intervals within complex graphemes, this research aimed to add to the growing body of literature on the interaction between linguistic processing and motor control. It offers insights into models of written word production by comparing handwriting and typing in a shallow orthography, while also accounting for the writer's level of experience with each modality.

Materials and method

Participants

A total of 72 participants without reported cognitive or learning disorders were recruited for this study, divided into two age groups: adults and adolescents. Both groups volunteered for the study and provided informed consent. Minors participated with parental consent. The adult group comprised university and doctoral students recruited at the University of Trento, Italy. The adolescent group consisted of 9th-grade students from a local high school. All participants were native Italian speakers, except for one adult who reported Hungarian as a second language, and five adolescents who reported Portuguese, Tunisian Arabic, or Albanian as a second language. Table 1 provides a detailed summary of participant characteristics for each group, including age, gender, handedness, and self-reported daily reading and writing habits across different modalities**.**

As shown in Table 1, adults reported spending similar daily time on handwriting and typing (paired t-test: $t_{(35)}=1.27$, $p=0.213$). Likewise, their reading time was comparable between paper and screens (paired t-test: $t_{(35)}=1.37$, $p=0.180$). Among adults, 22 participants indicated being more accustomed to typing than handwriting, while the remaining reported the opposite. Adolescents predominantly used handwriting in school activities, with typing limited to sporadic lessons (e.g., informatics). As detailed in Table 1, they reported spending significantly more daily time on handwriting than typing (paired t-test: $t_{(35)}=7.06$, $p<0.001$), and more time reading on paper than on screens (paired t-test: $t_{(35)}=9.05$, $p<0.001$).

To further assess differences in experience between the two groups, their self-reported daily reading and writing habits were compared using independent t-tests. Results, also reported in Table 1, indicated that adults engaged more in reading on

Table 1 Participant Demographics and Self-Reported Daily Reading and Writing

Characteristic	Adult group (N=36)	Adolescent group (N=36)	Statistical comparison
Age (years)	23.58 (2.91)	14.75 (0.65)	
Gender (num. females)	21	22	
Handedness (num. right-handed)	33	35	
Time spent on handwriting (min/day)	170.11 (170.64)	354.36 (144.19)	$t=-4.99$, $p<0.001$
Time spent on typing (min/day)	215.42 (163.11)	137.19 (163.11)	$t=2.30$, $p=0.025$
Time spent reading on paper (min/day)	222.00 (170.59)	314.31 (164.50)	$t=-2.34$, $p=0.022$
Time spent reading on screen (min/day)	275.69 (228.65)	90.00 (74.28)	$t=4.63$, $p<0.001$
Whole-word durations in handwriting (ms)	3111.68 (1144.82)	3555.10 (1321.11)	$F=13.04$, $p<0.001$
Whole-word durations in typing (ms)	1003.88 (533.90)	1612.30.01 (814.69)	$F=65.21$, $p<0.001$

Data are presented as Mean (SD)

screens and typing activities than adolescents, whereas adolescents spent more time reading on paper and handwriting compared to adults. Furthermore, a direct comparison of whole-word durations —the time required to write or type an entire stimulus from the first to the last pen/key press— in handwriting and typing experimental dictation tasks (see Task and procedure for details) was conducted using ANOVA, which revealed that adolescents were slower than adults, especially in typing. None of the participants, except for one adult, had received formal instruction in touch typing in the past.

The study utilized a subset of data previously collected in two separate works with different analyses and theoretical questions (adults in Cerni & Job, 2022, and minors in Cerni & Job, 2023).

Tasks and procedure

Before the experimental session, participants completed an in-person questionnaire about their reading and writing habits. They reported how many minutes per day they spent (a) handwriting, (b) typing on a standard keyboard, (c) reading on paper, and (d) reading on screens, specifying whether these activities were for school/work or pleasure. This information is provided in the Participant section (see Table 1). After completing the questionnaire, participants carried out two dictation tasks: one using a pen and the other using a keyboard. The order of the tasks was counterbalanced, with half of the participants starting with the pen and the other half with the keyboard. All participants took part in individual sessions in a quiet room at the presence of the experimenter.

During the handwriting task, participants were presented with an auditory stimulus for each trial and wrote it directly onto the tablet's surface (see Apparatus) on a designated line displayed at the center of the screen. They were instructed to use uppercase letters, which naturally encouraged pen lifts between characters, facilitating the analysis of ILIs (e.g., Kandel et al., 2006a, 2006b). Participants controlled the timing of each trial using the pen to tap a virtual red arrow placed at the end of the line to receive the next stimulus.

In the typing task, participants typed the given stimuli using a physical keyboard. As they typed, the letters were displayed sequentially in the center of the tablet screen, replicating the experience of a standard word processor. They pressed the return key to receive the next stimulus. Participants were informed that using the backspace key would be treated as an error, though it remained functional. This approach was chosen to prevent data loss, minimizing the potential impact of unnecessary corrections.

Although no strict time constraints were imposed, participants were prompted to perform the tasks both quickly and accurately. To ensure clarity and familiarity with the tools, four practice trials preceded both the typing and handwriting tasks.

Stimuli

The dictated stimuli included 32 items divided in two separate lists: one for words and one for pseudowords. Participants alternated between these lists across conditions (typing and handwriting). The stimuli incorporated orthographic complexities unique to Italian, involving digraphs with vowel-dependent pronunciations. Specifically, [k] and [ʃ] are written as<ch>and<sc>, respectively, before the vowels *e* or *i*. Additionally, [ʎ] is represented by<*gl*>followed by *i* while [ɲ] is consistently spelled<gn>, regardless of the subsequent vowel. The orthographic complexities were always positioned in the final syllable of the stimuli. The first letter of each orthographic digraph (*ch*, *gl*, *gn*, *sc*) corresponded to the initial letter of the last syllable, ensuring that the complexity was structurally and phonologically tied to the terminal syllable and that the first letter of the complexity was preceded by a syllable boundary as always occurs in Italian (e.g., pe-*sc*e [*fish*]).

Pseudowords were derived by altering 1–2 letters in short words and 2–3 letters in long words, ensuring they matched the original words in syllable structure and retained the same orthographic complexity in the last syllable. Words and pseudowords included an equal number of short (5–6 letters) and long (8–9 letters) stimuli. Additionally, they were balanced across several linguistic and task-related factors, including orthographic neighborhood size, bigram frequency, letter frequency, average strokes per letter, and the number of hand transitions between sides of the keyboard (according to touch-typing method). The complete lists of stimuli are available at: https://osf.io/sqmnp/. During the tasks, participants also wrote other items, includ ing simple stimuli and items with different complexities, which were not analyzed in this study (see Cerni & Job, 2022, 2023 for complete lists).

Apparatus

Data collection was carried out using a Samsung Galaxy Book 12" tablet PC (60 Hz refresh rate), running a 64-bit version of Windows 10 Pro (1903). For the handwriting tasks, the tablet was placed horizontally on a desk in tablet mode, where participants used the S-Pen—a stylus with a 0.7 mm tip and pressure sensitivity of 4096 levels, providing a sampling frequency of 240 Hz. For the typing task, the device was set in desktop mode with a customized physical keyboard. Stimulus presentation and response recording were managed using OpenSesame 3.2.7 (Mathôt et al., 2012) for the typing task, and Eye and Pen 3.0.0–13 (Alamargot et al., 2006) for the handwriting tasks. The acoustic stimuli, recorded by a male native Italian speaker, were presented to participants through headphones.

Data preparation and statistical analysis

Before the analysis, we excluded stimuli that were either misspelled or included corrections that would prevent accurate calculation of ILIs. Additionally, we removed data that presented technical issues during the ILI inspection process. Specifically, for the adult participants, 4.7% of the handwriting data and 8.0% of the typing data were removed, while for the adolescents, 13.5% of the handwriting data and 16.5% of the typing data were excluded. Final dataset is available at: https://osf.io/sqmnp/.

For the data analysis, we measured the ILIs at three critical points within the stimuli: between the letter preceding the orthographically complex digraph and the first letter of the digraph (Syllable-Boundary-ILI —which always correspond to a syllable boundary, see Stimuli), between the two letters comprising the digraph (Digraph-

ILI), and between the last letter of the digraph and the following letter (Post-Digraph-ILI). For instance, in the word *pesce* [*fish*], where the orthographic complexity lies in the *sc* digraph, we measured the ILIs at three points: the Syllable-Boundary-ILI corresponded to the interval between *e* and *s*, the Digraph-ILI corresponded to the interval between *s* and *c*, and the Post-Digraph-ILI corresponded to the interval between *c* and *e*. In this study, inter-letter intervals (ILIs) were calculated as the time between two successive keystrokes in typing tasks (referred to in previous research as interkey or keystroke intervals, as detailed in Crump & Logan, 2010; Logan & Crump, 2011; Waes et al., 2021) or the pen lifts (pressure = 0) between consecutive letters in handwriting tasks (following the method from Kandel et al., 2006a, 2006b).

The statistical analysis was conducted using R (Version 4.4.1; R Core Team, 2024) with linear mixed-effects models, implemented via the *lmerTest* package (Version 3.1–3; Kuznetsova et al., 2017). To meet the assumptions of normality and improve model fit, the dependent variables (ILIs) were log-transformed. The model included fixed effects for lexicality (words and pseudowords), ILI position (Syllable-Boundary-ILI, Digraph-ILI, and Post-Digraph-ILI), task modality (handwriting and typing), and group (adults and adolescents, a between participants effect), along with their interactions. The scaled length of the stimulus was included as a control variable to account for potential differences in the number of letters across stimuli, but it did not reach significance and was removed from the final model. For random effects, random intercepts and slopes were specified for participants and stimuli. The final model included random intercepts and a by-participant random slope for lexicality and task modality. Other random slopes were not included due to issues with overparameterization or singularity (Bates et al., 2015; Matuschek et al., 2017).

Model selection followed a stepwise backward elimination approach (through *step* function in lmerTest package), starting with the four-way interaction (Lexicality × ILI position × Task modality × Group). Lower-order interactions were evaluated sequentially, retaining significant effects according to the Akaike Information Criterion (AIC). The principle of marginality was applied, ensuring that all lower-order interactions and main effects present in significant higher-order interactions were retained in the model. To assess the significance of the fixed effects and their interactions, a Type III Analysis of Variance (ANOVA) was performed on the final model. The Satterthwaite method was used to approximate the degrees of freedom, with the results reported as *F*-values and corresponding *p*-values to determine the impact of each predictor. For significant interactions, customized pairwise contrasts of estimated marginal means with Bonferroni adjustment were computed using the *emmeans* package (Version 1.10.4; Lenth, 2023). Graphical representations of the estimated marginal means, and standard errors were generated using *effects* package (Version 4.2–2; Fox & Weisberg, 2018) and *ggplot2* package (Version 3.5.1; Wickham, 2016). R codes to reproduce the results can be found at: https://osf.io/sqmnp/.

Table 2 Results of the analysis of variance for fixed effects in the final model

Fixed effects	Sum of squares	Mean square	df	DenDF	F value	*p*-value
Lexicality	0.48	0.48	1	39.2	3.03	0.090
ILI position	309.55	154.78	2	12,049.9	978.48	<0.001
Task modality	8.00	8.00	1	69.9	50.60	<0.001
Group	7.10	7.10	1	70.0	44.89	<0.001
Lexicality* ILI position	3.03	1.52	2	12,050.0	9.58	<0.001
ILI position* Task modality	14.98	7.49	2	12,049.9	47.34	<0.001
ILI position* Group	3.33	1.66	2	12,049.9	10.52	<0.001
Task modality* Group	4.01	4.01	1	69.9	25.33	<0.001
ILI Position* Task modality* Group	3.52	1.76	2	12,049.9	11.13	<0.001

Degrees of freedom (df) refer to the number of levels or groups for each factor, while denominator degrees of freedom (DenDF) correspond to the error term and are calculated using the Satterthwaite approximation

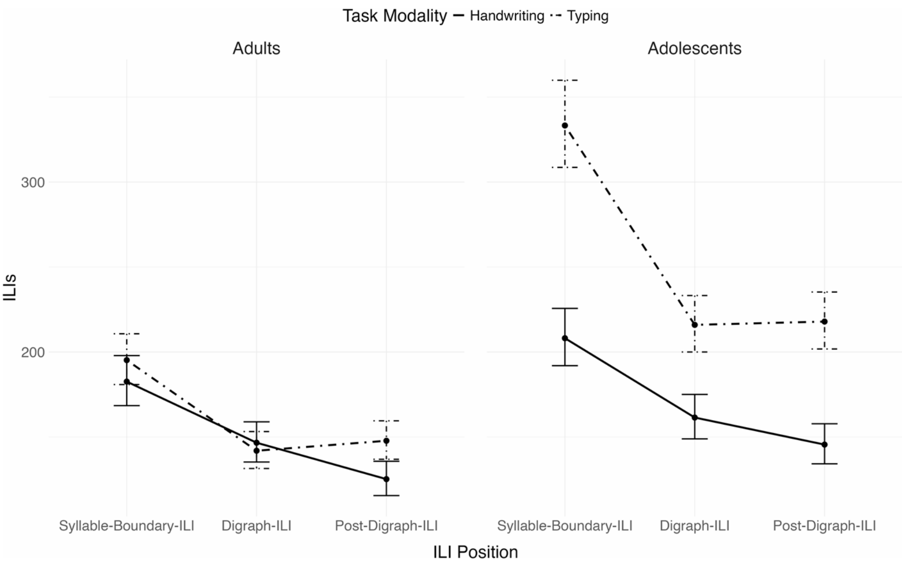

Fig. 1 ILIs (estimated effects in ms) for the interaction between ILI position, Task modality and Group. Error bars show confidence intervlas. *ILI*: Interletter Interval

Results

Descriptive statistics of the collected ILIs, organized by ILI position, task modality, and group, are reported in the Supplementary Materials, Table S1. The results of the final linear mixed-effects model are summarized in Table 2. Supplementary Materials Table S2 provides the summary of the model. The analysis retained a significant three-way interaction between group, task modality, and ILI position. Figure 1 illustrates this interaction, showing the estimated ILIs for adults (left panel) and adolescents (right panel) across handwriting and typing at the three key positions before, within, and after the digraphs.

This interaction qualified lower order terms and provides insights into how orthographic complexity is processed and executed during handwriting and typing (RQ1) across age groups (RQ2). Regarding handwriting, post-hoc comparisons releveled that both adults and adolescents progressively accelerated ILIs when executing the complexity. Specifically, both groups exhibited a significantly slower Syllable-Boundary-ILI compared to the Digraph-ILI (adults: $t=12.95$, $p<0.001$; adolescents: $t=14.29$, $p<0.001$), which in turn was followed by a slower Post-Digraph-ILI (adults: $t=9.31$, $p<0.001$; adolescents: $t=5.83$, $p<0.001$). However, adolescents took significantly longer to execute the Post-Digraph-ILI ($t=2.65$, $p=0.030$) compared to adults. No significant group difference was observed for the Syllable-Boundary-ILI ($t=2.30$, $p=0.072$) and for the Digraph-ILI ($t=1.69$, $p=0.283$).

For typing, the overall pattern was consistent across age groups, but more pronounced in adolescents, and showed differences compared to handwriting. Specifically, the Syllable-Boundary-ILI was significantly slower than the Digraph-ILI (adults: t=18.38, $p<0.001$; adolescents: t=23.94, $p<$ 0.001). Notably, this difference was more accentuated in typing than in handwriting. Furthermore, unlike handwriting, typing did not exhibit a faster transition from the digraph to the subsequent vowel: for adults, the Post-Digraph-ILI showed a trend towards being slower than the Digraph-ILI, though this difference was not statistically significant ($t=-2.32$, $p=0.061$). In adolescents, no difference emerged between these intervals ($t=-0.49$, $p=1.000$). However, the Post-Digraph-ILI remained significantly faster than the Syllable-Boundary-ILI for both groups (adults: $t=16.06$, $p<0.001$, adolescents: $t=23.46$, $p<0.001$). Regarding the differences between age group, adolescents exhibited longer durations for all typing intervals compared to adults, including the Syllable-Boundary-ILI ($t=9.95$, $p<0.001$), Digraph-ILI ($t=7.81$, $p<0.001$), and Post-Digraph-ILI ($t=7.22$, $p<0.001$).

As for lexicality, the final model did not reveal significant interactions between lexicality and either task modality or group, indicating that words and pseudowords elicited comparable ILIs across these conditions. However, an interaction between lexicality and ILI position emerged, revealing that writing pseudowords required significantly more time to initiate the complexity (Syllable-Boundary-ILI: $t=3.46$, $p=0.001$) compared to writing words. Nevertheless, no significant differences were observed in the Digraph-ILI ($t=0.83$, $p=0.412$) nor in the Post-Digraph-ILI ($t=0.37$, $p=0.713$), suggesting that the lexical status primarily influences the preparatory processes associated with orthographic complexity or, more in general, with the final syllable.

Discussion

The results of the study highlighted distinct patterns of motor planning and execution of the orthographic complexity that reflected both task-specific demands and individual differences in experience with handwriting and typing.

The first research question (RQ1) aimed to explore the similarities and differences between writing modalities in processing and executing the complex digraphs. As predicted, the ILIs preceding the digraph were longer in duration compared to subsequent ILIs, as they occurred at syllable boundaries, points where linguistic processing prepares upcoming graphemes (e.g., Kandel & Valdois, 2006; Weingarten et al., 2004). This effect was more pronounced for pseudowords than for words, reinforcing the notion of an anticipatory planning of orthographic units: engaging the sublexical route, as required for pseudowords, demands greater cognitive effort in planning compared to lexical access, whan orthographic representations are programmed more efficiently and rapidly.

Notable differences emerged between modalities in the transition from digraph execution to the subsequent vowel. Specifically, in handwriting Post-Digraph-ILIs were significantly faster than the preceding complex ILI, a speeding-up that was absent in typing. This contrast supported the hypothesis that modality-specific differences arise from distinct strategies for processing orthographic units. According to the dual-route model of spelling, graphemic representations are stored in the graphemic buffer are syllable-based and include complex graphemes processed as unified units rather than sequences of individual letters (Houghton & Zorzi, 2003; Rapp et al., 2002). The observed acceleration in handwriting suggested that either the entire syllable was programmed in advance or that the complex grapheme and the following vowel were pre-planned as a cohesive orthographic unit (Spinelli et al., 2012), aligning with cascading execution (Kandel, 2023). In Italian, this interpretation is particularly plausible given that the vowel specifies the identity of the digraph (e.g., in *sce, gli*). However, the absence of a control condition without orthographic complexity prevented us from determining whether the faster Post-Digraph-ILI reflected syllable-level pre-programming or the retrieval of a smaller digraph–vowel unit. Furthermore, the locus of programming may lie within the execution of individual letters—a possibility not addressed in the present study (see Limitations).

In contrast, the lack of this effect in typing points to a more segmented processing style, where the digraph and the subsequent vowel are treated as distinct components. Nevertheless, it is important to note that Post-Digraph-ILI remained significantly faster than the Syllable-Boundary-ILI, suggesting that, even in typing, syllables were likely programmed at a higher level than the individual graphemes (Kandel et al., 2011; Weingarten et al., 2004). While typing allows for more anticipatory planning than handwriting, making possibile to preprocess orthographic complexity before the onset of a complex syllable (Cerni & Job, 2022; Logan & Crump, 2011), it also requires bimanual coordination, fine finger control, and often visual guidance depending on expertise. Although each keystroke is mechanically simple, orchestrating multiple effectors and maintaining alignment with linguistic planning increases cognitive load (Rumelhart & Norman, 1982). These combined demands when encountering orthographic complexity may hinder smooth transitions between letters, particularly for less skilled typists (e.g., Cerni et al., 2016a, 2016b; Pinet et al., 2022).

The aforementioned consideration aligns with findings related to the second research question (RQ2), which confirmed developmental differences in digraph execution. Although the overall trends in the two modalities were comparable between groups, notable distinctions highlight that linguistic processing of adolescents was more affected by their less automatized handwriting and, especially, typing skills (see Participants for details on these skill differences). In the handwriting dictation task, adolescents required significantly more time during the Post-Digraph-ILI compared to adults. Nevertheless, this ILI was significantly faster than the ILI within the complexity, suggesting that the orthographic units planned at the syllable boundary encompassed both the digraph and the subsequent vowels. This planning, being less efficient in adolescents, resulted in less smooth transitions compared to adults. The finding supports the hypothesis that less experienced writers struggle with the dynamic integration of orthographic complexity during motor execution (Kandel & Perret, 2015). In reference to this, it is important to specify that linguistic processing might have occurred during letter execution in adolescents, given their longer handwriting duration (see Participants) but similar ILI durations compared to adults.

In the typing task, adolescents displayed significantly slower execution across all collected ILIs compared to adults. Of particular importance was the more pronounced difference in the duration of the Syllable-Boundary-ILI for adolescents, indicating greater effort in initiating the syllable execution and planning the complexity. Furthermore, while adults tended to be slower in transitioning from the complex digraph to the following vowels, adolescents maintained a more stable velocity. This finding confirms that, even in less experienced typists, orthographic units are planned differently than in handwriting. Additionally, the inherently segmented nature of typing may exacerbate these challenges for less experienced typists, particularly when processing complex graphemes and following key presses. This reflects less efficient integration of orthographic and motor planning.

Limitations

The current findings must be interpreted with some limitations in mind. The tasks and measures selected may not fully capture the complexity of writing and typing behaviors. In this study, we focused on interletter intervals, concentrating on the letter selection process. However, the definition of ILIs differs between handwriting and typing. In handwriting, an ILI typically represents the pause between writing individual letters, whereas in typing, it reflects the time interval between two consecutive keypresses, including the time to press the first key, which could be considered part of letter execution. Crucially, spelling processes occur not only during ILIs but also concurrently with letter execution (e.g., Kandel et al., 2006a, 2006b). Thus, the slower interval observed after the digraph in typing, compared to the interval between letters composing the digraph, might manifest as slower letter durations in handwriting, for example in the final letter of the digraph.

A critical limitation of this study is the absence of a control condition featuring stimuli devoid of orthographic complexity. Without such a baseline, we are unable to definitively ascertain whether the digraph and the subsequent vowel are processed and programmed as a unified motor sequence within each writing modality. While our primary research objective was to directly compare handwriting and typing modalities, we recognize the potential for deeper insights through more refined analyses. Future studies could benefit from employing stimuli with carefully controlled syllabic structures and systematically varying digraph positions within these stimuli.

Additionally, our study focused on 9th-grade adolescents, who may not represent broader experiences with the two writing modalities. Future research should include a wider age range and assess more performance variables to better understand the interaction between linguistic and motor processes as skill automatization increases in both handwriting and typing. Notably, Italian students often lack access to typing instruction, leading to less comparable typing data across ages, while handwriting offers a more standardized basis for comparison, as it is closely aligned with linguistic development. This discrepancy should be considered when comparing writing modalities, as limited typing instruction can affect the generalizability of results. Furthermore, future studies should include balanced samples in terms of gender and handedness, to mitigate for potential bias and better capture a more robust understanding of how these variables interact with writing modalities and skill development. Additionally, as this study used auditory stimulus presentation, potential effects of input modality on orthographic planning cannot be ruled out. Comparing auditory and visual presentation could clarify their influence. A comprehensive exploration of how motor and linguistic skills develop across diverse contexts is crucial for revealing the evolution and interdependence of these skills throughout educational and developmental stages.

Conclusions

This study explored the influence of orthographic complexity on letter selection during handwriting and typing, specifically focusing on the temporal dynamics of interletter intervals within Italian digraphs. The findings offer new insights into how linguistic processing and motor control interact across different writing modalities, with individual experience shaping these processes. Handwriting allows for more integrated planning of syllables comprising complex digraph, whereas typing involves more segmented planning, suggesting different strategies for processing orthographic units. Significantly, although their execution patterns were similar to adults, adolescents required greater effort and cognitive resources for motor planning when executing digraphs in typing, their less practiced modality.

The implications of these findings are significant for our understanding of written word production across different writing modalities. Linguistic processing during motor execution, which involves the planning and maintenance of orthographic sequences in memory, is influenced by the cognitive and motor features of handwriting and typing. Furthermore, developmental stages shape how orthographic units are planned and executed across modalities. These insights open new avenues for adapting models of written word production. Generally, seminal models of language production consider spelling and less extensively the peripheral processes of writing. These latter processes demonstrated to alter the linguistic processing. Furthermore, updated models of writing production consider less typing than handwriting. This gap in modeling highlights the need to account for the unique characteristics of each writing modality. For example, extending a robust model like APOMI (Kandel, 2023) to typing would require accounting for its unique motor constraints, including the discrete, sequential nature of keystrokes as opposed to the continuous movement characteristic of handwriting. Educationally, these results highlight the importance of addressing the distinct cognitive and motor demands of handwriting and typing when designing writing instruction—recognizing that the two modalities engage orthographic planning differently and may support literacy development in complementary ways (e.g., Cerni et al., 2025; Malpique et al., 2023, 2024; Spilling et al., 2022, 2023).

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Author contributions Tania Cerni conceived and designed the study, including the development of the methodology. She was responsible for preparing materials, collecting data, and conducting formal analyses. Additionally, she drafted and finalized the manuscript.

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Data availability Materials and code to reproduce the results are available at https://osf.io/sqmnp/.

Declarations

Conflict of interest The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval The study was approved by the Ethical Committee of the University of Trento (protocol: 2019-008).

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