

Learning by writing: The influence of handwriting and typing on novel word learning in typically developing readers and readers with dyslexia

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ARTICLE INFO

Keywords:

Handwriting

Typing

Dyslexia

Orthographic learning

Semantic learning

ABSTRACT

Background: Writing-based spelling is crucial for acquiring written word knowledge, contributing to form lexical representations that integrate motor information. Modern educational settings incorporate multiple modalities, with typing increasingly complementing handwriting. However, evidence on their relative effectiveness in supporting orthographic and semantic learning, particularly when these processes are impaired, remains limited. **Aims:** This study examines the impact of the two writing modalities on the learning of orthographic and semantic information in typically developing (TD) children and those with developmental dyslexia (DD). **Sample:** Eighteen Italian middle school students with DD and eighteen age-matched TD readers participated.

Methods: Participants learned a set of nonwords, varying in transcription regularity, paired with images, either through typing or handwriting. Their spelling and nonword-image association skills were then tested. Recorded metrics included accuracy, writing duration during learning and spelling tasks, and reaction time in the nonword-image mapping task.

Results: TD children benefited from both writing modalities during learning. Crucially, the DD group showed better spelling and nonword-image association performance when learning occurred through typing. Accuracy in retrieving orthographic and semantic information was not significantly affected by the time spent handwriting or typing during learning. Performance differences based on transcription complexity provided insights into the extent to which children internalized lexical representations.

Conclusions: Both writing modalities can support orthographic and semantic learning, but the complex graphomotor demands of handwriting may hinder novel word acquisition in dyslexic individuals. Incorporating typing into educational strategies could alleviate the cognitive load associated with handwriting and enhance word retention for these students.

1. Introduction

Within the framework of many educational systems, the foundational practice of handwriting endures as the primary medium of written expression for students, from early childhood to late adolescence. Although some schools are increasingly incorporating keyboard-based writing instruction, sometimes introducing it before teaching handwriting (Gamlem et al., 2020; Hultin & Westman, 2013; Spilling et al., 2023), its formal teaching use remains limited (Berninger et al., 2015; Malpique, Valcan, Pino-Pasternak, Ledger, Asil, et al., 2023; Malpique, Valcan, Pino-Pasternak, Ledger, & Kelso-Marsh, 2023; Poole & Preciado, 2016; Weigelt-Marom & Weintraub, 2018). Despite this,

keyboard-based digital devices are becoming common in educational settings, playing a pivotal role in fostering inclusivity for children with specific learning disabilities (Morphy & Graham, 2012). In the current landscape, analog and digital writing modes coexist, and children often acquire both handwriting and typing skills, even if with different developmental trajectories (e.g., Cerni & Job, 2023). While training in handwriting and typing, young students concurrently learn to spell and read, thereby enhancing their vocabulary, and advancing their written language skills.

In this study, we focus on whether handwriting and typing contribute differentially to lexical acquisition within the alphabetic system, providing distinct sensorimotor experiences for words through different

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motor actions and consequent attentional and time constraints in producing letters. We examined a sample of middle school students with reading and spelling disabilities alongside age-matched peers with typical development. Our research is based on the hypothesis that different writing experiences, combined with varying reading and spelling abilities, influence the construction of lexical representations that integrate phonological, orthographic, and semantic information about words.

1.1. Learning novel words through writing

Learning a new (written) word entails the integration of phonological, orthographic, and semantic information into a unified lexical representation stored in memory (e.g., Ehri, 2005; Perfetti & Hart, 2002). This integrated representation not only facilitates the rapid recognition of the word while reading – automatically accessing the lexical representation from the visual perception of the letter string – but also enables fast retrieval during spelling, when the letter string is recalled from memory (Perfetti, 1997).

The process leading to the construction of a cohesive representation of the phonological and orthographic word form, commonly referred to as *orthographic* or *lexical learning*, is often attributed to a self-teaching mechanism (Share, 1995). When encountering a newly introduced word, the cognitive effort invested in identifying letter identity, letter position, and phonological recoding implicitly establishes a connection between the word's orthographic form and its corresponding phonological code (for reviews, see Li & Wang, 2022; Nation & Castles, 2017). With repeated exposure to the word, this association between distinct linguistic representations becomes increasingly effortless, transitioning from a deliberate effort to a fast and automatic process (Ehri, 2005). According to the lexical quality hypothesis (Perfetti & Hart, 2002), fully specified lexical representations integrate a semantic component. This implies that learning the meaning of new written words during reading – also known as semantic learning – is essential to support word reading and reading comprehension (Ehri, 2014; Ricketts et al., 2008).

Though less investigated, spelling is also a means for orthographic learning, potentially surpassing reading in efficacy due to its demand for heightened attention to individual letters and their corresponding sound (Perfetti, 1997). Empirical evidence indicates that writing-based spelling practice contributes significantly to enhancing word orthographic knowledge when compared to reading (Conrad et al., 2019; Li et al., 2020; Ouellette, 2010; Shahar-Yames & Share, 2008; Solier et al., 2019; Zemlock et al., 2018). For instance, Bosse et al. (2014) compared the effect of handwriting training and spelling-aloud training on the construction of orthographic representations of novel words in French 5th-grade children, assessing their performance in written production and recognition tasks. Handwriting training significantly enhanced orthographic learning in the production task. Thus, multisensory feedback – visual, motor, and proprioceptive – involved in planning and graphically producing orthographic sequences supports the acquisition of orthographic information more effectively than perceptual and articulatory movements alone.

The idea that writing motor acts contributes to learning finds support in neuroscientific studies that show activations in motor areas during letter perception (James, 2010, 2017; James & Atwood, 2009; James & Gauthier, 2006; Li & James, 2016; Longcamp, Anton, et al., 2005; Longcamp et al., 2003). For instance, Longcamp et al. (2003) showed that the visual perception of letters and their motor production engaged the same area in the premotor cortex. Overall, these studies show that orthographic representation may consist of a multifaceted network encompassing not only visual (and auditory) information but also a crucial sensorimotor component acquired through the concurrent learning of reading and writing.

Regarding semantic learning, the presence of orthographic information facilitates vocabulary acquisition compared to phonological information alone (Balass et al., 2010; Colenbrander et al., 2019).

However, surprisingly, no studies have examined whether writing training further enhances the integration of phonological, orthographic, and semantic representations. According to connectionist models, word reading — particularly lexical reading — relies on the rapid and dynamic coordination of phonological, orthographic, and semantic processes (see e.g., Plaut, 1999 for review). These models suggest that as an orthographic representation becomes more accessible through the lexical route, its connections to phonological and semantic information strengthen, facilitating word recognition and comprehension. Therefore, investigating whether not only the mere presence of orthographic information but also the active experience of writing contributes to the consolidation of semantic representations is a key focus of the present study.

1.2. Handwriting and typing in letter and word acquisition

As emphasized in the opening lines of our introduction, handwriting is not the sole transcription modality used during written language acquisition. The integration of typing into educational curricula, often as a self-taught modality, underscores its potential impact on integrated lexical representations. Both handwriting and typing entail the execution of motor patterns, albeit with significant differences in their motor-perceptual mechanisms. Interacting with the pen involves a tangible graphomotor experience emphasizing the intricate form of letters and demanding attention to both their identity and formation. On the contrary, interacting with the keyboard involves the repetitive execution of motor patterns where hand and arm movements are associated with key positions. During this process, attention dynamically shifts between the keys and the screen (Mangen & Velay, 2010). Thus, while handwriting involves the gradual processing of both lexical and sublexical linguistic information as the motor execution unfolds, in typing, linguistic processing appears to be more anticipatory to the flow of keypresses, aligning with its faster motor execution (Cerni & Job, 2022). The diverse nature of the motor actions and linguistic processing in the two modalities is manifested in the different neural areas engaged in recovering handwriting and typing motor patterns (Purcell et al., 2011) and is reflected in the corresponding cognitive demands (Bouriga & Olive, 2021).

Typing is often regarded as a less motor-demanding writing modality, primarily because it lacks the intricate processes of letter form programming and execution associated with handwriting (Cerni & Job, 2022; Mangen & Velay, 2010; Spilling et al., 2022). Therefore, studies focusing on letter and word acquisition started from the underlying assumption that typing contributes differently, and potentially less strongly, to the learning process compared to handwriting (e.g., Kiefer et al., 2015; Mangen & Balsvik, 2016; Mangen et al., 2015; Mayer et al., 2020; Wiley & Rapp, 2021). However, similar to handwriting, typing practice affects both letter and word recognition, particularly in expert touch typists where stable motor patterns are well-established (Beilock & Holt, 2007; Cerni, Velay et al., 2016; Van den Bergh et al., 1990; Yang et al., 2009).

Letter knowledge demonstrates more pronounced improvements in both production and recognition when individuals undergo handwriting training as opposed to typing. These improvements are observed both in behavioral outcomes and neural processes (Li & James, 2016; Longcamp et al., 2008; Longcamp, Zerbato-Poudou, & Velay, 2005; Wollscheid et al., 2016). Notably, examining studies that explore letter or word training on subsequent word perception and production unveils less consistent evidence. Some studies suggest that handwriting is more powerful for orthographic learning (Cunningham & Stanovich, 1990; Kiefer et al., 2015; Mangen et al., 2015), while others fail to discern significant differences between the two writing modalities (Mayer et al., 2020; Ouellette & Tims, 2014; Suggate et al., 2023; Vaughn et al., 1992). For instance, Mayer et al. (2020) showed that, although handwriting letter training improved subsequent letter recognition, typing yielded comparable performance to traditional handwriting in reading and

writing words composed of the trained letters. Furthermore, [Ouellette and Tims \(2014\)](#), in a study where young participants explicitly trained on whole words during the learning phase, revealed no differences between the two writing modalities in orthographic recall; however, participants with stronger preexisting typing skills demonstrated better performance for words learned through typing. This finding underscores the importance of considering participants' prior experience and proficiency with both handwriting and typing, as these factors may moderate the impact of the writing modality on orthographic learning.

In summary, both handwriting and typing contribute to orthographic learning but there is limited conclusive evidence favoring one modality over the other. While there is robust evidence supporting the idea that handwriting enhances letter knowledge, evidence is scarce regarding the effectiveness of training that involves acquiring orthographic patterns and integrated lexical representations through both typing and handwriting. To our knowledge, no studies have investigated whether writing practice — and differences between these practices — affects not only orthographic processing but also the formation of more comprehensive lexical representations that include word meaning. Understanding this relationship could provide a more complete perspective on the role of handwriting and typing in sight word reading ([Ehri, 2005](#)) and the quality of lexical representations ([Perfetti & Hart, 2002](#)). Moreover, previous studies involved preschoolers or young students in primary grades with limited or no experience with word spelling. Additionally, these participants often had minimal exposure to using the pen and very limited familiarity with the keyboard. This limitation hinders the generalizability of findings on orthographic learning, especially concerning older students who are more accustomed to both handwriting and typing.

1.3. Orthographic learning in dyslexia: a role for handwriting and typing?

Individuals with dyslexia demonstrate poor phonological processing and storage ([Boada & Pennington, 2006](#); [Vellutino et al., 2004](#)) but they also exhibit weaknesses in orthographic processing and knowledge ([Manis et al., 1993](#); [Zarić et al., 2021](#)). The persistent difficulties in mapping phonological and orthographic forms, coupled with difficulties in storing them in memory, suggest that dyslexic children fail in orthographic learning ([Nation & Mak, 2020](#)). In acquiring new lexical representations, they need more word repetitions, and their performance does not reach the same standard as those observed in typical developing peers (e.g., [Alt et al., 2017](#)).

Research exploring the impact of writing practice on word learning in dyslexia is limited and dated. [Vaughn et al. \(1992, 1993\)](#) found poorer performances in dyslexic children compared to primary-grade controls, but they did not find a significant difference between typing and handwriting training in orthographic learning. Additionally, [Berninger et al. \(1998\)](#), controlling for the orthographic complexity of the to-be-learned stimuli, reported no overall differences between the two writing modalities in improving word spelling memorization in both children with and without spelling difficulties. Notably, they found an improved performance after handwriting training in learning to spell words with higher grapheme-to-phoneme correspondence, and an advantage of typing training for more complex words. The authors proposed that when the grapheme-to-phoneme correspondence is high, attentional resources are more concentrated on the writing motor plan. In contrast, when the grapheme-to-phoneme correspondence is not predictable, attention is more focused on selecting orthographic units, and the intricate handwriting motor plan becomes a potential interference.

The challenges dyslexic individuals face in writing planning and execution offer valuable insights into their role in word learning. Impaired orthographic processing in people with dyslexia influences handwriting fluency, as evident in the slowed graphomotor movements when writing words with complex orthography ([Kandel and Spinelli, 2010](#); [Kandel et al., 2017](#)) and in longer pauses when writing sentences

([Sumner et al., 2013, 2014](#)). Furthermore, graphomotor difficulties and atypical handwriting development may be associated with dyslexia, even in the absence of specific motor deficits. Specifically, individuals with dyslexia showed a lower quality in handwriting words with higher graphic complexity (i.e., with abrupt changes in pen stroke trajectory, [Gosse & Van Reybroeck, 2020](#)) as well as an overall lower letter legibility in comparison to typical developing peers ([Berninger et al., 2008](#)). Hence, the motor pattern involved in handwriting could pose challenges in interaction with weak spelling processing (see also [Danna et al., 2022](#)). Consequently, it is plausible to consider this interaction as a potential source of difficulties in word acquisition. Given the scarcity of studies on typing, especially considering dyslexia, it remains inconclusive to assert that this writing modality may have a different impact than handwriting.

1.4. The present study

Considering the literature review provided in this introduction, we can summarize some open questions regarding the effects of handwriting and typing on lexical development. First, writing plays a central role in lexical acquisition, with handwriting being particularly relevant for letter learning; however, there is no clear evidence supporting the superiority of either handwriting or typing for word learning in orthographic acquisition. This is especially true for the dyslexic population, for whom existing studies are outdated and inconclusive. Second, while previous research has primarily focused on orthographic learning, semantic learning has been largely overlooked. This raises the question of whether writing practice can influence the consolidation of word meaning. Third, most studies have examined young children with limited experience in spelling, handwriting, and typing. However, experience with writing may play a crucial role in the acquisition of novel words.

To address these gaps, the present study aims to compare the effects of handwriting and typing practice on both orthographic and semantic learning in two groups of participants: children with developmental dyslexia and typically developed readers. All children were enrolled in Italian middle school (6th to 8th grades) and, in addition to having the expected knowledge of spelling rules – taught in primary school in Italy –, had a solid foundation in handwriting and basic typing proficiency. While Italian schools provide formal handwriting instruction, they lack structured curricula for typing ([MIUR, 2012; 2018](#)). As a result, typing skills are typically developed through individual practice, as in many other European countries ([Grabowski, 2008](#); [Pinet et al., 2022](#)). To ensure that our sample had experience with both modalities, we selected middle school children, assuming that students at this age generally use keyboards for personal activities. We also collected information on their writing habits and assessed their fluency in both writing modalities, including during the experimental tasks, as described later.

During the training procedure, participants were instructed to try to learn a set of nonwords presented both orally and visually, paired with corresponding images of the referents, by transcribing them. Each participant learned half of the novel items through handwriting and half through typing. We manipulated the linguistic status of the to-be-learned nonword stimuli and included both regular nonwords (with 1-to-1 phoneme-to-grapheme correspondence) and ambiguous nonwords (with two possible transcriptions). This approach allowed us to explore how different writing modalities impact the acquisition of orthographic and semantic information for items that vary in spelling complexity. Italian, a shallow orthography, is highly predictable for reading but poses difficulties in spelling due to a certain degree of ambiguity and context-sensitive rules, a characteristic shared with many other alphabetic languages ([Caravolas, 2004](#)). The ambiguities arise from homophonic sounds that can be represented by multiple orthographic forms, of which only one is correct (see [Angelelli et al., 2008](#); [Marinelli et al., 2009](#) for a detailed discussion). For instance, the phoneme sequence [kw] may be written as *cu* (e.g., *cuore* – heart), *qu* (e.g., *quadro* –

painting), or, less frequently, *cqu* (e.g., *acqua* – water), depending on the word. Similarly, the phoneme [je] can be spelled as *sce* (e.g., *pesce* – fish) or *scie* (e.g., *scienza* – science). In these cases, lexical knowledge plays a crucial role in retrieving the correct orthographic structure during spelling as phonological-to-orthographic conversion rules are insufficient for accurate spelling.

During transcription, we measured the time taken to write the nonwords from the first to the last pen/key press (Whole Response Duration, WRD), assuming it to be an indicator of automaticity in both handwriting and typing, as more fluent responses reflect greater proficiency in writing and spelling processing (e.g., Cerni & Job, 2023; Kandel & Perret, 2015). Additionally, since handwriting is typically more time-consuming than typing, WRD also serves as a measure to control for exposure time to the novel word. We measured and analyzed WRD during the learning session, examining group differences in executing stimuli with varying orthographic complexity.

During the testing phase, to assess orthographic learning, participants completed a spelling-to-dictation task, writing all the words they had learned through both modalities. This was done to detect whether a specific writing modality enhances orthographic recovery when the testing modality is congruent or whether acquired spelling knowledge is generalizable to both testing modalities (e.g., Masterson & Apel, 2006). Additionally, to test for possible differential effects in integrating semantic and orthographic information during learning, participants were asked to match a referent image (semantic information) with its correct paired nonword visually presented (orthographic information), selecting the correct option from four alternatives in a nonword-image mapping task. In addition to accuracy in spelling-to-dictation and nonword-image mapping, we also examined the influence of the learning modality (handwriting and typing) on the timing of responses. Specifically, in the spelling-to-dictation task, we measured WRD, expecting that more fluent responses indicate more proficient spelling recovery of the learned nonwords. Furthermore, in the nonword-image mapping task, we considered response times (RT) as a measure of the degree of learning, reflecting the reading process and the decision time. Importantly, we included WRD measured during the learning phase in our statistical models to assess the effects of writing modality on word learning beyond the time spent writing, considering its potentially different impact on the two participant groups.

We designed the study based on the hypothesis that both handwriting and typing can serve as effective means for novel word learning in a population of students familiar with Italian spelling rules, primarily accustomed to handwriting but also experienced in typing. In line with e.g., Ouellette and Tims (2014), we did not expect to observe differences between the two modalities in retrieving spelling and semantic information at least in typically developing children. Regarding dyslexic children, one might anticipate that handwriting, due to its longer and more detailed planning and execution, could lead to better performance (e.g., Wollscheid et al., 2016). On the other hand, while typing requires the development of automaticity, often through autonomous training, its motor demands are lower than handwriting. This could potentially mitigate the difficulties associated with handwriting in dyslexic individuals (e.g., Gosse & Van Reybroeck, 2020), particularly when dealing with complex words (e.g., Berninger et al., 2008) and thus facilitate better lexical acquisition following typing practice.

In line with our hypotheses, we predicted higher accuracy in the spelling-to-dictation and image-mapping tasks for nonwords — particularly ambiguous ones — learned through typing in dyslexic children. These predictions were made while controlling for potential interference from writing duration during learning, measured through WRD in the learning phase, which serves as an index of motor experience in handwriting and typing as well as the time devoted to learning the words. Conversely, if the motor act of handwriting strengthens lexical representations, we would expect handwriting to provide a facilitative effect. Regarding timing measures, we expected to observe similar effects than the one observed for accuracy, i.e., increased fluency when the

nonwords were better recalled. However, we predicted a strong impact of WRD during learning on WRD during spelling, demonstrating continuity in fluency between learning and testing. Such a result would indicate that spelling processing during writing is influenced by the proficiency demonstrated during learning, and not necessary to the writing modality used.

Finally, regarding the transcription complexity of the nonwords, it is well established that during writing acquisition, children struggle to associate phonological forms with their correct orthographic representations. Italian individuals with dyslexia, in particular, exhibit persistent difficulty in detecting phonologically plausible errors (i.e., pseudohomophones; Marinelli et al., 2009) and frequently produce similar errors in spelling (Angelelli et al., 2004). Therefore, we predicted that words with a regular orthographic structure would be easier to learn, both in terms of response time and accuracy, than those with a more complex structure. This effect should be more pronounced in children with dyslexia, who experience difficulties in integrating orthographic and semantic representations, a process that is crucial for comprehensive lexical acquisition (Nation & Mak, 2020). However, given the handwriting difficulties reported in dyslexia, typing may support the reinforcement of ambiguous word representations in this group.

To sum up, the study had the main objective to understand the contribution of handwriting and typing on lexical acquisition in children with dyslexia and typically reading children who have experience with both writing modalities. This was examined by considering (1) modality constraints, which encompass not only the intrinsic differences in motor acts but also factors such as the time allocated for writing during learning, and (2) the orthographic complexity of the novel words. Findings hold the potential to reveal the role, whether facilitative or not, of planning and execution processes of handwriting and typing for students still expanding their vocabulary, even if not in the initial stages of reading and spelling instruction. Moreover, the results may provide additional insights into spelling and writing difficulties faced by the dyslexic population, who are often introduced to the computer as an assistive tool (Morphy & Graham, 2012), even if the impact of typing practice on their vocabulary improvement remains unclear.

2. Materials and methods

2.1. Participants

Thirty-six middle school children volunteered in the study under parental written consent. Eighteen of the participants had a formal diagnosis of Developmental Dyslexia (DD group, 8 females). They were recruited in two Italian health public centers accredited to release formal certification of Specific Learning Disorders. Seven participants in this group attended Grade 6, four Grade 7, and seven Grade 8. We did not include children with certified graphomotor difficulties (dysgraphia or motor coordination disorders) and all of them had normal intelligence (certified by formal testing). The remaining 18 participants were age-matched readers with Typical Development, with no history of reading and spelling difficulties (TD group, 11 females). They were recruited in a public school in Trieste, Italy. Eight participants in this group attended Grade 6, three Grade 7, and seven Grade 8. Teachers confirmed the absence of any learning difficulties and normal intelligence. None of the participants had neurological or psychiatric conditions, nor did they have cognitive or physical impairments. They spoke Italian as their first language and had been attending schools in Italy since infancy. Three DD participants had one or both bilingual parents (speaking Chinese, Serbian, or Romanian).

As displayed in Table 1, the two groups did not statistically differ in age, dexterity index (collected through the Edinburgh Handedness Inventory; Oldfield, 1971), and verbal memory span (Digit Span scaled score from the WISC-IV; Orsini et al., 2012; Wechsler, 2003). To control for reading and spelling competencies, we administered the Word Reading, Nonword Reading, Word Spelling, and Nonword Spelling

Table 1

General description of the two groups. Mean, standard deviation (in brackets), and Mann-Whitney test (*U* test). TD: Typical Development, DD: Developmental Dyslexia.

	TD group	DD group	<i>U</i> test
Age (months)	150.89 (10.60)	150.72 (11.49)	170
Dexterity index	0.62 (0.52)	0.68 (0.47)	145
Digit Span (scaled score)	10.89 (1.97)	9.50 (2.81)	213
Word reading (sylls/sec)	4.52 (0.66)	2.02 (0.71)	324***
Word reading (errors)	0.67 (0.77)	8.22 (6.16)	21***
Nonword reading (sylls/sec)	2.83 (0.48)	1.31 (0.47)	302***
Nonword reading (errors)	1.44 (1.34)	9.24 (5.27)	26.5***
Word spelling (errors)	0.00 (0.00)	2.76 (2.28)	36***
Nonword spelling (errors)	0.50 (0.62)	3.76 (1.68)	6.5***
Daily reading time on paper (self-report)	3.94 (0.80)	3.22 (1.06)	220.5
Daily reading time on PC (self-report)	3.22 (1.00)	2.39 (1.14)	226.5
Daily writing time with pen (self-report)	4.39 (0.70)	3.83 (1.29)	195.5
Daily writing time with keyboard (self-report)	3.11 (1.02)	2.61 (1.09)	201
PC use (self-reported years)	3.86 (2.38)	2.86 (1.72)	200.5
Handwriting fluency (letters/min)	99.33 (19.58)	76.72 (15.78)	266**
Typing fluency (letters/min)	153.89 (51.17)	97.67 (34.72)	265**

Note. Digit Span corresponds to the age-based, norm-referenced scaled score derived from the sum between Digits Forward and Digits Backward row scores (Orsini et al., 2012; Wechsler, 2003). Word reading and Nonword reading (sylls/sec) correspond to the total number of syllables in the lists divided by the time taken to read them (Sartori et al., 2007). Reading and spelling errors correspond to the sum of errors committed in each subtest (z-scores were not present in the normative data, but only categorical labels). None of the participants in the TD group obtained scores below the norms. In the DD group, all participants except two obtained error scores equal to or below the 10th or 5th percentile in the reading subtests, and all participants except three obtained error scores equal to or below the 10th or 5th percentile in the spelling subtests. Handwriting fluency and typing fluency correspond to the number of legible letters written over 1 min in the subtest “sequences of numbers” (BVSCO 2, Tressoldi et al., 2013) performed with the two writing modalities. ***p* < .01, ****p* < .001.

subtests from the Italian clinical battery *DDE-2: Batteria per la valutazione della Dislessia e Disortografia Evolutiva* (Developmental Dyslexia and Dysorthography Battery 2, Sartori et al., 2007). These subtests are commonly used in Italy as part of the clinical assessment of reading and spelling disabilities, addressing both lexical and sublexical difficulties (Associazione Italiana Dislessia, 2009). Table 1 shows the score of reading time (syllables per second) and the number of errors for the reading and spelling tests. As expected, the two groups statistically differed in the reading and spelling measures. Individual scores for each participant can be found at <https://osf.io/98xwe/>.

To control for handwriting and typing habits, we collected self-reported information on the daily frequency of reading and writing with computers and with pen and paper by asking questions such as “During a typical day, how often do you read (or write) with the computer (or pen & paper)?”. Participants responded on a 5-point Likert scale as follows: (1) “Never or almost never”, (2) “Rarely”, (3) “Sometimes”, (4) “Often”, (5) “Always or almost always”. To enhance the reliability of the responses, participants were guided by the experimenter during the administration of the questionnaire to ensure proper understanding. The questions were read aloud and clarified as needed, helping minimize misunderstanding. The data collected are presented in Table 1. The two groups did not show differences in their reading and writing habits. We also examined within-group differences in the time allocated to reading and writing with computers and pen and paper. Both groups wrote more with the pen than with the keyboard (Wilcoxon signed rank test, TD group: *W* = 10, *p* = .002; DD group: *W* = 13.5, *p* = .008), and read more on paper than on screen (TD group: *W* = 87, *p* = .024; DD group: *W* = 74.5, *p* = .042). We also asked participants to

identify which of the two writing modalities they used most frequently. All participants answered ‘pen’, except for three participants in the TD group and four in the DD group, who answered ‘keyboard’. Groups did not differ in the number of years using the computer. Overall, participants reported using the computer mainly for home and leisure activities, while relying on pen and paper for school-related tasks. All participants typed with two hands, typically using 1–2 fingers per hand, as observed by the experimenter.

Additionally, we collected quantitative measures of typing and handwriting fluency by administering the subtest 4b (“Numbers in letters”) from *Batteria di Valutazione della Scrittura e della Competenza Ortografica 2* (BVSCO 2 Tests for assessing writing and orthographic competence, Tressoldi et al., 2013). The test requires writing from memory the ordered sequence of numbers in letters for 1 min, and the total number of legible graphemes serves as an index of writing fluency. While the test was originally designed for assessing handwriting, we utilized it for assessing typing as well (the order of the typing and handwriting tests was counterbalanced between participants). This approach enabled us not only to compare handwriting and typing proficiency within and between groups but also to ensure that all children were familiar with typing and did not exhibit handwriting legibility issues or experience excessive writing fatigue. Children were asked to handwrite in uppercase letters, and during typing, Caps Lock was set on (for details on the font used in the experimental tasks and its motivation, see section 2.3). The DD group was slower in both writing modalities compared to the TD group (see Table 1). When comparing the two writing modalities within each group, both demonstrated faster performance in the typing test compared to the handwriting test, with the difference being more pronounced in the TD group (TD group: *W* = 6, *p* < .001; DD group: *W* = 29, *p* = .015).

2.2. Stimuli

Thirty-two 2-syllable nonwords (5–6 letters) were designed for the study (see the complete lists at <https://osf.io/98xwe/>). They adhered to Italian orthographic rules and differed according to transcription complexity. Half of the nonwords had a regular transcription (1:1 phoneme-to-grapheme correspondence) and the other half had an ambiguous transcription (i.e., more than one orthographic solution is plausible). We selected four phonetic groups with two possible orthographic solutions in Italian: [kw] transcribed as *cu* or *qu*, [je] transcribed as *sce* or *scie*, [tje] transcribed as *ce* or *cie*, and [dʒe] transcribed as *ge* or *gie*. For each phonetic group, we created four nonwords, two for each orthographic transcription (e.g., for the sound [je], two nonwords were written as *sce* and two as *scie*). The phonetic groups were evenly distributed between the first and last syllable, with an equal distribution of positions across the stimulus categories (e.g., for the phoneme [je] the nonwords were *scedo*, *sciera*, *nescie*, *lusce*). Regular nonwords were constructed respecting the syllabic structures of ambiguous nonwords.

The stimuli were divided into two lists (List1 and List2), one presented in the handwriting learning condition and the other in the typing learning condition, counterbalancing the list order between participants within groups (see section 2.3 for task details). Each list contained 8 nonwords with regular transcription and 8 nonwords with ambiguous transcription (two nonwords for each phonetic group, one for each orthographic transcription).

Nonwords were balanced for a set of linguistic and task-related variables known to affect writing. A set of 2 x 2 factorial design ANOVAs with transcription complexity, List, and their interaction as independent variables confirmed the absence of statistical differences (all *ps* < 0.05). Table S1 in Supplementary Materials reports descriptive statistics of the controlled variables.

Each nonword was paired with a referent image corresponding to a novel object extracted from the Novel Object and Unusual Name (NOUN) Database (Horst & Hout, 2016). Familiarity score (percentage of adults that declare to have seen the object before) and Name-Ability

score (percentage of adults that spontaneously give the same name to the object), provided by NOUN Database, were balanced between lists and transcription complexity (2 x 2 factorial design ANOVAs, all $ps < 0.05$). Details are reported in Supplementary Materials [Table S1](#).

2.3. Tasks and procedure

The experimental session took place in a quiet room at either the health center or the school where the participant was recruited. Each participant performed the tasks during an individual session lasting approximately 50 minutes, under the guidance and supervision of the experimenter (the first author). Pause sections were provided between tasks and during each task, and participants were allowed to take breaks as needed. None of the participants reported excessive fatigue during the tasks, nor did they exhibit illegible handwriting or unusually slow typing. Each participant completed two experimental phases: a learning phase and a testing phase. The typing and handwriting fluency tests were collected at the beginning of the experimental session, allowing the participants to familiarize themselves with the equipment (described in section 2.4). Reading and spelling control subtests were administered at the beginning or the end of the session. The phases were separated by a pause of approximately 10–15 min during which the experimenter collected participant information – i.e., dexterity index, reading and writing habits –, and the Digit Span score. Details on these tests are reported in section 2.1, while the Learning phase and the Testing phase are described below. [Fig. 1](#) displays a graphical schematization of the experimental tasks.

2.3.1. Learning phase

During this phase, participants had to try to memorize the 32 stimuli by copying them from the computer screen. They wrote half of the nonwords with the pen (handwriting condition) and half with the keyboard (typing condition), counterbalancing the lists of stimuli between participants and groups. The starting writing modality was alternated between participants in each group (see Supplementary Materials, [Table S2](#) for information on the task order). Participants were informed that in a subsequent testing phase, they would be required to spell the nonwords and recognize the nonword-image association.

In each trial, a fixation cross stayed at the center of the screen for 500 ms replaced, at the offset, by the orthographic form of the stimulus in uppercase letters (Verdana font, size 100 pixels) and by the image, positioned above the nonword. Simultaneously, the auditory form of the stimulus was presented. A rectangular empty box of 800 x 150 pixels appeared under the orthographic form. The participants were instructed to pay attention to the auditory and orthographic inputs and the corresponding referent and to copy the stimulus in the box. In the handwriting condition, participants wrote directly on the screen with a special pen (details are in section 2.4) in uppercase letters. To move to the next trial, participants pressed the pen on a red arrow displayed at the right of the box. In the typing condition, they typed on a standard

keyboard while the letters appeared in uppercase in the designed box, one at a time, as in normal word processors. Participants pressed the Return key to move to the next trial. The choice of uppercase letters aimed to align the written outputs as closely as possible to the orthographic inputs in both conditions (lowercase was not chosen as it is not systematically taught in all Italian schools, and, if learned, it is usually abandoned during the second grade in favor of cursive).

In each learning condition, nonwords were presented four times in four separate blocks of trials. In each block, nonwords appeared in random order. A self-regulated pause was inserted every 9 trials. At the beginning of each learning condition, participants practiced the task with four trials presenting real words to ensure the procedure was clear.

2.3.2. Testing phase

This phase was designed to test the orthographic and semantic memory of the learned nonwords. Participants were asked to type and handwrite all the nonwords under dictation (regardless of the learning condition) reproducing the learned orthography. Then, they performed a nonword-image mapping task.

Spelling-to-dictation tasks. Two versions of the same task were administered: a handwriting task and a typing task. The order of the two tasks was counterbalanced between participants in each group (see Supplementary Materials, [Table S2](#)). Each trial started with a 500-ms fixation cross, followed by the auditory form of a stimulus. Concurrently, the same rectangular box presented in the learning phase was displayed and participants used it to either handwrite or type the heard stimulus. Then, they proceeded to the next trial following the same procedure as in the learning phase. All the stimuli were presented both in the handwriting task and the typing task, in random order (i.e., 32 trials in each testing condition). A self-regulated pause was inserted every 9 trials. Participants were encouraged to write the nonwords respecting the original orthography and to use uppercase letters. Each testing condition started with four practice trials with real words.

Nonword-image mapping task. This task followed the writing tasks. Participants were presented with the learned images one at a time and had to choose the corresponding nonword between four alternatives. The four alternative nonwords included two orthographic forms learned through handwriting and two learned through typing, equally distributed between transcription complexity. In each trial, after a 500-ms fixation cross, the image appeared at the center of the screen. Four boxes, each displaying a written nonword were presented at the corners of the image. The target nonword appeared equally often in each of the boxes. Participants answered by touching directly on the screen the item they identified as the correct referent. Images were presented once, in random order, for a total of 32 trials. The task started with four practice trials presenting real words.

2.4. Equipment

All the computerized tasks were administered on a 12-inch tablet PC

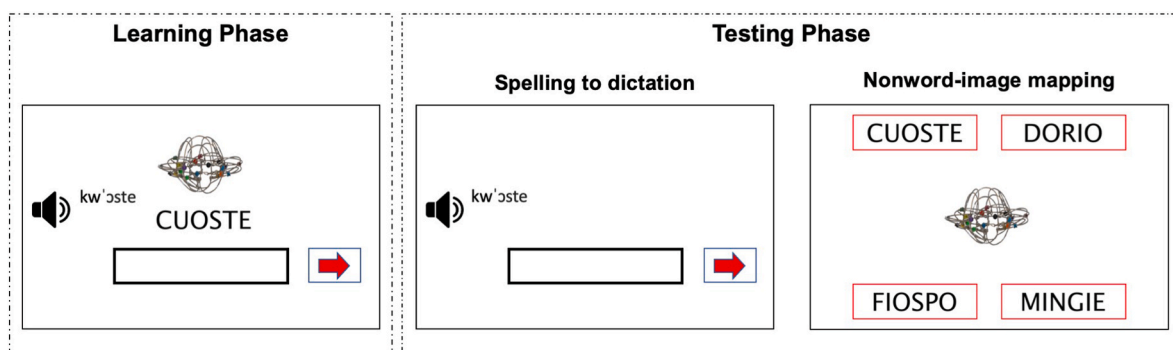


Fig. 1. A graphical schematization of the tasks in the Learning and Testing phases.

(Samsung Galaxy Book, refresh rate: 60 Hz, Operating System: Windows 10 Pro 1903). For handwriting, the tablet PC was placed horizontally on the desk (like a paper sheet). Stimulus presentation and response collection were programmed through Eye and Pen 3.0–13 (Alamargot et al., 2006). The mean sampling rate was 240 Hz. Participants handwrote on the tablet with the S Pen, a specific pen customized for the tablet PC, with a small 0.7-mm tip and ergonomically equal to a standard pen. We asked participants their opinion on their handwriting sensation: most of the participants described the pen as “similar to a normal pen”. Only 6 participants (3 in the DD group and 3 in the TD group) described it as “more mechanical” or “strange”. In the typing condition, a customized physical keyboard was connected to the tablet PC settled in the desktop modality. Stimulus presentation and response collection were programmed through OpenSesame 3.2.7 (Mathôt et al., 2012). This software was also used to present and record the nonword-image mapping task. Acoustic forms of the stimuli were registered with Google Cloud Text-to-Speech software, with a Wavenet Italian female voice. They were presented through headphones.

2.5. Data analysis

2.5.1. Statistical power

We performed a sensitivity analysis through PANGAEA — Power Analysis for General ANOVA design (Westfall, 2016)— testing a mixed design with two random factors (participants and stimuli). Fixed factors were Group (TD vs DD) as a between-subject factor, Learning condition (handwriting vs typing) as a within-subject factor and between-item factor, Transcription complexity (regular vs ambiguous) as a within-subject and between-item factor, and Testing condition (handwriting vs typing, tested only for spelling task) as a within-subject and within-item factor. We inserted in the simulation also the interactions within all the fixed factors. Results showed a power ranging from 0.85 (for nonword-image mapping task) to 0.99 (for spelling-to-dictation tasks, considering both testing conditions in the same model) with a medium effect size ($d = 0.45$).

2.5.2. Data processing and preparation

In the learning phase, for each stimulus, we collected the Whole Response Duration (WRD), i.e., the time the participant took to copy the stimulus from the first to the last pen/key press (see Cerni & Job, 2022, 2023). In calculating WRD, we excluded stimuli with spelling errors and stimuli in which participants went back during writing to correct, add, or delete letters (a total of 6.73 % of the trials). This allowed us to analyze only nonwords that were correctly copied and that did not receive extra attention during writing (i.e., trials with corrections). The measure was reliable, with internal consistency coefficients for aggregated items across blocks as follows: Cronbach's alpha ($\alpha = 0.95$ and Lambda 6 ($\lambda-6 = 1.00$) (coefficients were calculated using the *alpha* function from the *psych* package; Revelle, 2024).

In the spelling-to-dictation task, we first discarded trials that were misspelled more than 2 times throughout the 4 blocks of the handwriting and the typing learning phase since we did not expect orthographic learning for those trials (6.19 % of the trials). Then, we annotated the accuracy of the written output as a binomial variable (1 = correct, 0 = error). We counted as errors handwritten and typed responses that did not correspond to the orthographic input we provided. The measure was reliable (internal consistency coefficients for aggregated items across testing conditions are: $\alpha = .77$, $\lambda-6 = 0.98$). We also measured the WRD for each trial, like in the learning phase, considering only correctly spelled responses and responses without backward corrections (27.13 % discarded trails). Internal consistency for WRD was: $\alpha = .72$, $\lambda-6 = 0.98$.

In the nonword-image mapping task, after removing trials that were misspelled more than 2 times in the learning phase (the same that were discarded in the spelling tasks), we collected accuracy as a binary variable. A trial was classified as correct if the target nonword was detected. Internal consistency was: $\alpha = .89$, $\lambda-6 = 0.97$. We also measured the

Response Time (RT) taken to select the correct nonwords, discarding trials with errors (i.e., incorrect image-word mapping, 45.36% of the trials). Internal consistency was: $\alpha = .89$, $\lambda-6 = 0.97$. Final datasets were available at: <https://osf.io/98xwe/>.

2.5.3. Statistical analysis

For all the analyses, we used R version 4.2.2 (R Core Team, 2022). We built linear mixed-effect models for continuous dependent variables (WRD and RT), which were log-transformed to approach normal distribution and to meet model assumptions. We built binomial logistic mixed-effect models with accuracy as a binary dependent variable. Participants and stimuli were set as random intercepts in all the models and continuous predictors were scaled. Models were implemented using the *lmerTest* packages (Kuznetsova et al., 2017). For significant interaction effects, we computed pairwise comparisons within groups (TD and DD) with Bonferroni adjustments through the functions *emmeans* for categorical predictors in *emmeans* package (Lenth, 2023). Details on model constructions for each task are provided in the following section (Results). The codes for reproducibility are available at: <https://osf.io/98xwe/>.

3. Results

Supplementary Materials Table S3 presents the observed means and linear correlations between the collected dependent variables (averaged across participants) for each group in the experimental tasks.

3.1. Learning phase

We were interested in analyzing whether the two groups differed in the time spent handwriting or typing nonwords — measured through WRD — during the learning phase and according to the transcription complexity of the stimulus. We fit a linear mixed model considering WRD as the dependent variable and as independent variables: Group (TD vs DD), Learning condition (handwriting vs typing), Transcription complexity (regular vs ambiguous), as well as their interactions. We inserted Block of trials (4 blocks as continuous predictors) as control predictor. To obtain the most parsimonious reduced model, we used the function *buildmer* (*buildmer* package, Voeten, 2023) which provided an automated backward stepwise selection and model reduction. We included by-participant and by-stimulus random intercepts and tested all possible slopes (maximal structure). Supplementary Materials Table S4 displays the terms retained in the final model.

The mixed-effects model analysis revealed a significant main effect of experimental Block ($\beta = -0.042$, $SE = 0.0028$, $t = -15.24$, $p < .001$), indicating an improvement in fluency over time.

A significant interaction between Group and Learning condition was found ($\beta = 0.259$, $SE = 0.098$, $t = 2.63$, $p = .013$), suggesting that handwriting was slower than typing for the TD group ($t = 2.67$, $p = .011$), whereas no difference was observed for the DD group ($t = -1.46$, $p = .154$). This interaction was further qualified by a significant three-way interaction between Group, Transition complexity, and Learning condition ($\beta = 0.067$, $SE = 0.025$, $t = 2.67$, $p = .008$). Pairwise contrasts showed no difference in transcribing regular and ambiguous nonwords in the TD group in the two writing modalities (handwriting: $t = -0.83$, $p = .411$; typing: $t = -0.18$, $p = .860$). In contrast, the DD group exhibited an increase in WRD for ambiguous words, but only in the typing condition (handwriting: $t = -1.00$, $p = .326$; typing: $t = -2.21$, $p = .034$).

3.2. Testing phase

3.2.1. Spelling-to-dictation task

With this task, we assessed if participants were able to retrieve the correct orthographic forms of the learned item according to the different learning conditions (handwriting or typing) and to the congruency between the learning condition and testing condition (handwriting and

typing during the spelling task). Additionally, we aimed to control whether the time spent writing the nonwords in the learning phase affected orthographic memory. To assess this, we utilized Learning time, i.e., the average WRD in the blocks of the learning phase for each nonword, as a continuous predictor. Our focus was on examining both accuracy in spelling retrieval and writing fluency measured by WRD. We present the accuracy and WRD results separately.

Accuracy. We built a generalized mixed-effect model with accuracy as a binary dependent variable using 3-block hierarchical regression. In each block, variables and interactions of interests are incrementally added as fixed effects during model steps, and these steps were compared through a likelihood ratio test. The resulting model in each block was reduced through backward selection, refitting it without predictors that did not reach significance to construct the most parsimonious model. Before proceeding to the next block, the reduced model of each block was compared with the final model of the preceding block (for a similar procedure see Cerni & Job, 2023; Scaltritti et al., 2019). Supplementary Materials Table S5 presents steps and results of the model selection for the spelling-to-dictation task.

In block 0, we added Group, Testing condition, and Transcription complexity (step 0.1) and their interactions (steps 0.2 and 0.3). In block 1, we incrementally added Learning time (step 1.1), its interactions with Group (step 1.2), Testing condition (step 1.3), and Transcription complexity (step 1.4). In block 2, we incrementally added Learning condition (step 2.1), its interactions with Group (step 2.2), Testing condition (step 2.3), and Transcription complexity (step 2.4). By selecting this block order, we aimed to infer the main effects and interactions between groups, testing condition and transcription complexity (block 0), to control for possible interference of learning duration (block 1), and to examine the effect of learning condition over and above all the other significant fixed effects (block 2). Models allowed by-participant and by-stimuli random intercepts. The random effect structure, including potential random slopes for key predictors, was systematically evaluated during model selection for each block.

In the final model, we finally allowed by-participant and by-stimuli intercepts. Random slopes were not included due to singularity or convergence failure. Table 2 presents the fixed effects retained in the final model, and Fig. 2, panel A, shows the graphical representation of the interaction of interest.

The main effect of Group indicated that DD group reached a generally lower accuracy than TD group in recovering the correct orthographic forms. The interaction between Learning condition and Group qualified this effect, suggesting that the impact of learning condition on orthographic recovery was different between groups. Results of pairwise contrasts between the two learning conditions within each group revealed that the DD group retrieved the orthographic form more accurately when nonwords were learned through typing than through handwriting, suggesting better spelling recall ($z = 2.32, p = .021$). In contrast, performance in the TD group was at ceiling in both learning condition ($z = -0.86, p = .392$).

As expected, nonwords with regular transcription were correctly spelled more often (accuracy estimated marginal mean: 0.98, CI [0.96,0.99]) than nonwords with ambiguous transcription (accuracy estimated marginal means: 0.60, CI[0.48,0.72]), with no interaction

Table 2
Fixed effects of the final model on accuracy in the spelling-to-dictation task.

Fixed effects	Estimate	SE	z	p
Intercept	4.166	0.353	11.816	<0.001
Group	-0.687	0.189	-3.628	<0.001
Transcription complexity	-3.465	0.417	-8.316	<0.001
Learning condition	-0.156	0.182	-0.857	0.392
Learning condition X Group	0.582	0.259	2.25	0.025

Note. SE: Standard Error. Reference levels for categorical predictor: Learning condition = Handwriting, Group = TD, Transcription complexity = regular.

with group and learning condition. Notably, the Learning time and Testing condition did not affect accuracy and were therefore discarded in model selections.

WRD. To construct the final model on WRD, we followed the same 3-block stepwise procedure described above for accuracy. The model included by-participant and by-stimulus random intercepts as well as by-participant random slopes for the effect of Testing condition and Transcription complexity and by-stimulus random slope for the effect of Testing condition. Supplementary Materials Table S5 reports the results of the model selections. Table 3 presents the fixed effects of the final models and Fig. 2 (panels B and C) shows graphical representations of significant interactions.

The final model did not retain Learning condition, indicating that the data did not provide evidence of a differential effect of practicing a novel word through handwriting or typing on WRD during the retrieval of the learned orthographic form, even when the learning and retrieval conditions were congruent (i.e., handwriting-handwriting, typing-typing). Notably, Learning time, which corresponds to the time spent handwriting or typing the nonwords during the learning phase, increased as WRD increases, suggesting that fluency in spelling reflected fluency during learning.

Groups showed different WRD patterns. Pairwise contrasts between testing conditions within each group (Fig. 2, panel B) showed that the TD group was slower at handwriting than typing ($t = 3.39, p = .002$), confirming the trend observed in the learning phase. In contrast, the DD group showed no difference in WRD between tasks ($t = -0.21, p = .833$). As evidenced by the interaction between Group and Transcription Complexity (see Fig. 2, panel C), the TD group showed increased writing duration when spelling ambiguous transcriptions compared to regular ones ($t = -3.14, p = .003$). In contrast, the DD group showed no differences due to Transcription Complexity ($t = -1.11, p = .275$).

3.2.2. Nonword-image mapping task

With this task, we investigated if participants were able to remember the image paired with the learned nonword, demonstrating semantic learning. Below, we discuss the accuracy and RT results separately.

Accuracy. Model construction followed the same block procedure as the spelling tasks (with the exception that, in the present task, the Testing condition was not a task-related variable and, thus, not included in model steps). Supplementary Materials Table S6 show the steps and results of the model selection procedure, while Table 4 shows the fixed effects retained in the final model. The final model retained by-participant and by-stimuli intercepts. Random slopes were not included due to singularity or convergence failure. The model Fig. 3, panel A, presents a graphical representation of significant interaction.

The main effect of Group indicated that DD group reached a generally lower accuracy than TD group in remembering the correct nonword-image association. The interaction between Learning condition and Group qualified this effect. Pairwise contrasts showed that the DD group was more accurate in recognizing the correct referent when it was previously learned through typing than handwriting ($z = -2.55, p = .011$) but there was no learning condition effect for the TD group ($z = -0.65, p = .518$). Neither the transcription complexity nor the learning time of the stimuli affected lexical acquisition.

RT. Model construction followed the same procedure for fixed-effect selection that was used for analyzing accuracy. Supplementary Materials Table S6 show the steps and the results of the model selection procedure, while Table 5 shows the fixed effects retained in the final model. The final model retained by-participant and by-stimuli intercepts, and by-participant random slopes for Transition complexity. Panel B and panel C in Fig. 3 present a graphical representation of significant interactions.

The DD group were generally slower in performing the task than the TD group. Considering the effects of the Learning condition, the parameters of the final model suggested a pattern similar to the one observed for accuracy (Fig. 3, panel B). The DD group was faster in

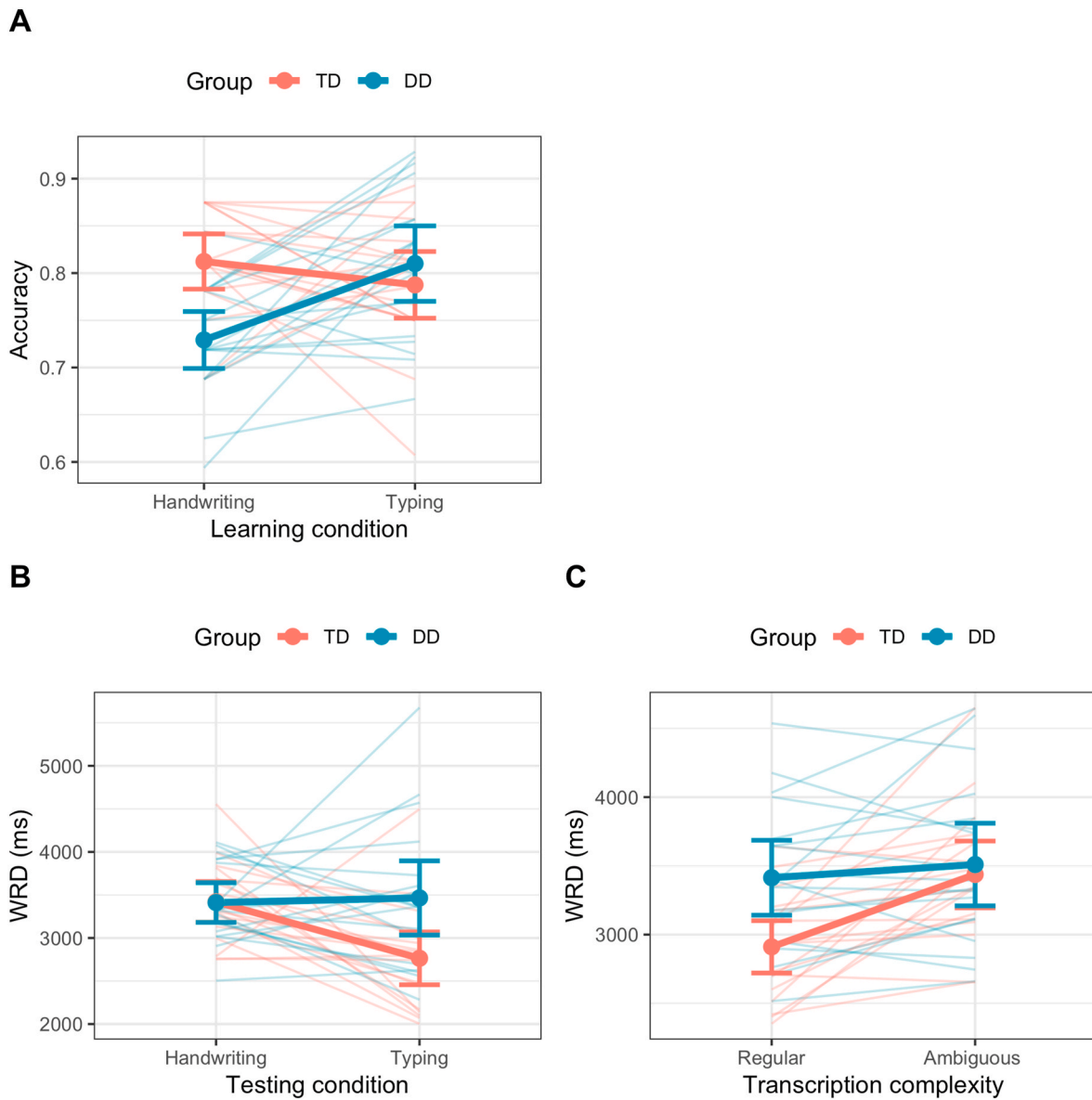


Fig. 2. Plots of the significant interactions in the final models of the spelling-to-dictation tasks. WRD: Whole Response Duration. TD: Typical Development. DD: Developmental Dyslexia. The plots show the Accuracy rate (row data) for the interaction Learning condition X Group (panel A), WRD (row data) for the interactions Testing condition X Group (panel B), and Transition complexity X Group (panel C). Error bars show 95 % confidence intervals. Transparent lines represent individual participant data.

Table 3

Fixed effects of the final model on WRD in the spelling-to-dictation tasks.

Fixed effects	Estimate	SE	<i>t</i>	<i>p</i>
Intercept	8.038	0.040	186.642	<0.001
Group	0.054	0.043	0.762	0.452
Transcription complexity	0.146	0.041	3.218	0.003
Testing condition	-0.189	0.018	-3.388	0.002
Learning time	-0.000	0.011	3.311	<0.001
Transcription complexity X Group	-0.090	0.027	-2.645	0.012
Testing condition X Group	0.180	0.026	2.676	0.011

Note. WRD: Whole Response Duration, SE: Standard Error. Reference levels for categorical predictor: Testing condition = Handwriting, Group = TD, Transcription complexity = regular.

recognizing the correct referent when learned through typing than through handwriting ($t = 2.64, p = .009$), while the TD group showed similar RTs in the two learning conditions ($t = -1.43, p = .154$).

Table 4

Fixed effects of the final model on accuracy in the nonword-image mapping task.

Fixed effects	Estimate	SE	<i>z</i>	<i>p</i>
Intercept	0.986	0.280	3.526	<0.001
Group	-1.587	0.373	-4.253	<0.001
Learning condition	-0.129	0.200	-0.646	0.518
Learning condition X Group	0.617	0.277	2.228	0.026

Note. SE: Standard Error. Reference levels for categorical predictor: Learning condition = Handwriting, Group = TD.

In terms of Transcription complexity, the two groups showed different RT patterns for regular and ambiguous nonwords (Fig. 3, panel C). The TD group was faster in recognizing the referent of regular than ambiguous nonwords ($t = -2.58, p = .003$), while no difference was observed for the DD group ($t = 0.63, p = .534$).

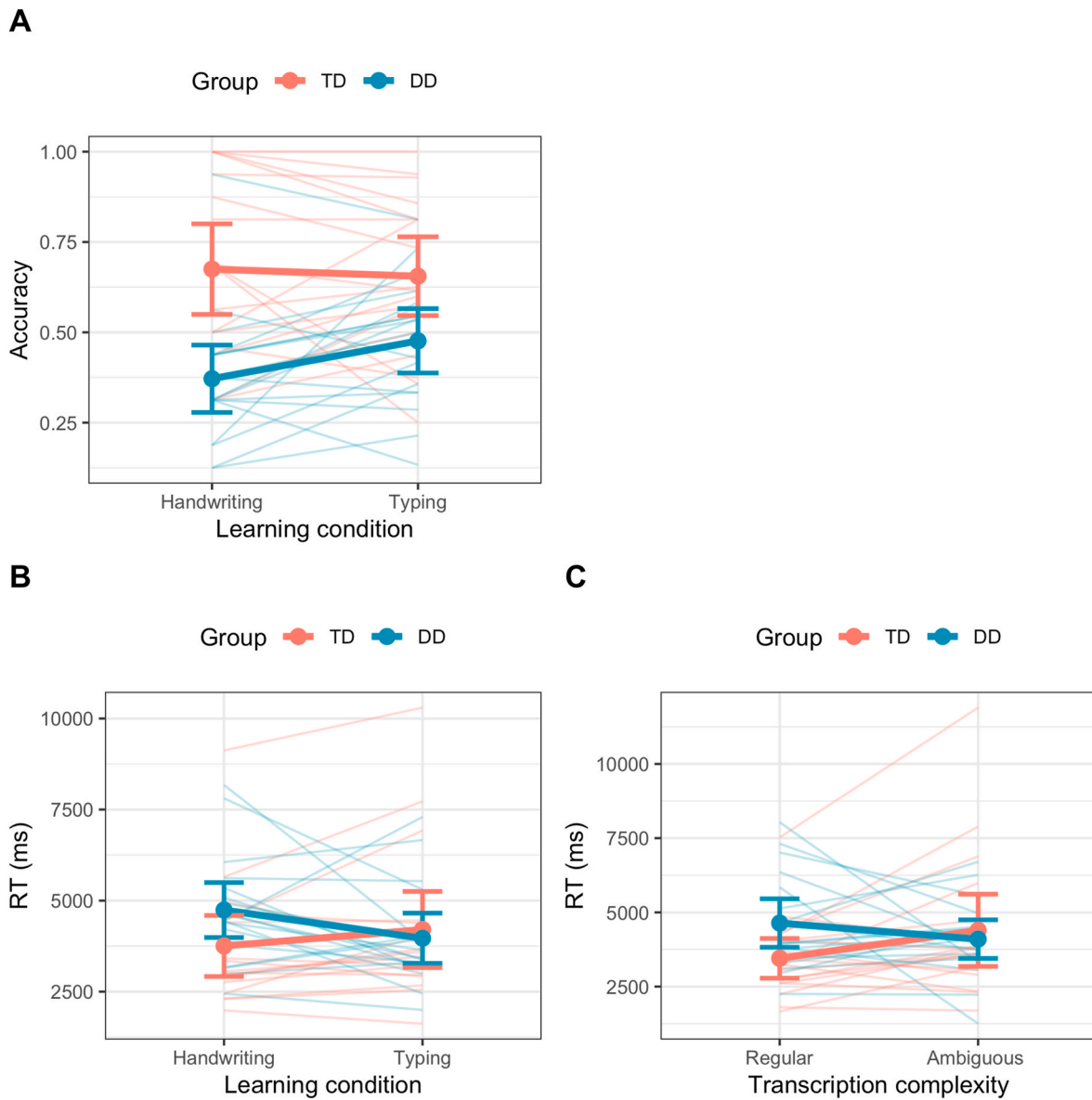


Fig. 3. Plots of the significant interactions in the final models of the nonword-image mapping task. RT: Response Time. TD: Typical Development. DD: Developmental Dyslexia. The plots show the Accuracy rate (raw data) for the interaction Learning condition X Group (panel A), RT (raw data) for the interactions Learning time X Group (panel B), Transcription complexity X Group (panel C). Error bars show 95 % confidence intervals. Transparent lines represent individual participant data.

Table 5
Fixed effects of the final model on RT in the nonword-image mapping task.

Fixed effects	Estimate	SE	<i>t</i>	<i>p</i>
Intercept	7.953	0.084	98.620	<0.001
Group	0.360	0.121	3.181	0.003
Transcription complexity	0.197	0.059	2.592	0.016
Learning condition	0.073	0.051	1.429	0.154
Transcription complexity X Group	-0.240	0.083	-2.318	0.028
Learning condition X Group	-0.242	0.084	-2.970	0.003

Note. RT: Response Time, SE: Standard Error. Reference levels for categorical predictor: Learning condition = Handwriting, Group = TD, Transcription complexity = regular.

4. Discussion

The current study aimed to compare the role of handwriting and typing in orthographic and semantic learning, focusing on 6th- to 8th-

grade dyslexic and typical readers with experience in both writing modalities. Specifically, we investigated how the writing modality used during novel word learning affects subsequent spelling and semantic retrieval, considering writing fluency (learning time) and transcription complexity. In the following sections, we discuss our results in detail, highlighting key observations regarding the (1) influence of writing modality and fluency during learning in integrating phonological, orthographic and semantic information, as well as (2) the impact of transcription complexity of the learned stimuli.

4.1. Examining the effect of handwriting and typing on orthographic and semantic learning

In the testing phase, we investigated spelling retrieval using a spelling-to-dictation task. In terms of spelling accuracy, the TD group demonstrated consistently high performance in retrieving correct orthographic representations, with no evidence of a difference based on the writing modality involved during learning. Conversely, DD readers

exhibited better spelling recall for nonwords learned through typing rather than handwriting. Importantly, typing practice improved their spelling accuracy to a level comparable to that of their peers (see Fig. 2, panel A). This finding suggests that typing offers certain advantages for dyslexic individuals in terms of orthographic retrieval, possibly due to the reduced motor demands compared to handwriting, which can be challenging for them (Berninger et al., 2008; Gosse & Van Reybroeck, 2020). This view is reinforced by the observation that the time spent transcribing nonwords during learning (Learning Time) did not influence spelling accuracy. Thus, the typing advantage in orthographic retrieval is not merely a consequence of the time spent spelling the words, meaning that fluency during learning — generally slower in handwriting for the TD group but comparable between handwriting and typing for the DD group — does not fully account for this advantage. Furthermore, the congruency between learning and testing modality did not affect spelling performance — as indicated by the absence of an interaction between Testing condition and Learning condition —, demonstrating that orthographic learning is generalizable and reflects a modality-free lexical representation (Masterson & Apel, 2006).

The facilitation of typing for dyslexic readers is not reflected in faster WRD during the spelling-to-dictation task, indicating that spelling fluency is not influenced by the learning modality, but rather by the WRD during the learning phase. Indeed, the pattern of handwriting and typing WRD during the spelling-to-dictation task mirrors that observed in the learning task: the TD group confirmed faster typing than handwriting, while the DD group achieved comparable handwriting fluency and typing fluency. These results, coupled with the significant linear correlations observed between learning and testing WRD and fluency test (see Supplementary Materials, Table S3), suggest that fluency during spelling retrieval relies more on general handwriting and typing skills than on a particular writing tool used during learning the novel words.

The nonword-image mapping task provided insights into semantic retrieval processes revealing aligned accuracy and response time (RT) patterns. Results mirrored the main findings observed for spelling accuracy. Specifically, the TD group showed no significant differences in accuracy and RT between learning conditions, suggesting comparable semantic retrieval following typing and handwriting practice. Conversely, DD individuals were more accurate and faster in recognizing the correct image referent for nonwords learned through typing compared to handwriting, suggesting that typing facilitated semantic integration for this group. In general, dyslexic children exhibited poorer performance (lower accuracy and slower RTs) than their peers in accurately matching images and their corresponding referents. However, their RTs improved after learning through typing bringing them closer to the level of their peers (see Fig. 3, panel B). This suggests that the processes involved in reading the nonword alternatives and selecting the correct one improved substantially. Notably, learning time did not influence task performance, indicating that the time allocated to writing novel words during the learning phase, as well as individual proficiency in handwriting and typing, did not account for the typing advantage observed in the DD group, nor did it confer any advantage to TD individuals.

To sum up, our findings show an advantage of typing in improving novel word learning for dyslexic readers. A specific difficulty in orthographic-motor integration — i.e., recalling and transcribing letter shapes and combinations without the allocation of cognitive effort (Christensen, 2005; Medwell & Wray, 2007) — is a proposed explanation for the struggles dyslexic children face in spelling and handwriting (Gosse & Van Reybroeck, 2020). In the current study, the difficulties experienced by DD individuals in orthographic and semantic learning, especially when writing manually, may be attributed to challenges in integrating phonological, orthographic, and semantic information while executing intricate motor tasks. The correlation between WRD and accuracy in the handwriting spelling task (see Supplementary Materials, Table S3), which was significant only for the DD group and only in the

handwriting condition, reinforces this perspective. On the contrary, avoiding the complexity of handwriting during novel word learning by opting for typing, appears to provide room for focusing on lexical acquisition. Finally, typical readers, who do not encounter challenges with orthographic-motor integration and possess experience with both typing and handwriting, did not exhibit superiority of one writing modality over the other.

4.2. Insights on the impact of transcription complexity

Both the spelling-to-dictation and nonword-image mapping tasks revealed interesting insights into the impact of transcription complexity on the nonwords learning. For both groups, spelling ambiguous nonwords increased the number of errors compared to regular nonwords, regardless of the learning modality. This contradicts the hypothesis that typing, due to its simpler motor plan, would facilitate the acquisition of more complex orthographic patterns by reducing motor interference compared to handwriting (Berninger et al., 1998). In fact, the advantage of typing for dyslexic children is independent of nonword complexity. Additionally, the impact of transcription complexity on spelling WRD was evident for the typical developing readers, as ambiguous nonwords were consistently written slower than regular ones. This finding aligns with previous research on the effect of Italian orthographic complexity on handwriting and typing fluency in dictation tasks in both adults (Cerni & Job, 2022) and adolescents (Cerni & Job, 2023), as well as in other languages (e.g., Afonso et al., 2015; Kandel & Perret, 2015; Pinet et al., 2016; Rønneberg & Torrance, 2019). However, dyslexic readers did not show differences in the writing duration between regular and ambiguous nonwords. As dyslexic readers struggle with automaticity in recognizing and recalling the correct orthography due to their underlying difficulties in phonological processing and orthographic memory (e.g., Vellutino et al., 2004; Zarić et al., 2021), in this task their difficulties may extend beyond ambiguity and involve broader challenges in orthographic processing of all the learned nonwords, included regular ones.

The image-mapping task prompts some important insights. While the effect of complexity on accuracy in retrieving semantic information was negligible, RT analysis revealed nuanced differences between the two groups. While the TD group had slower RTs when matching ambiguous nonwords compared to regular ones — consistent with the expected recognition delay of complex orthographies (e.g., Burani et al., 2006) —, no such distinction was evident in the DD group. This mirrors their spelling performance and, combined with generally lower RTs for the DD group compared to the TD group, suggests that dyslexic readers struggle to process recently learned orthographic information, both regular and ambiguous.

Italian dyslexics exhibit similar deficits in both lexical and sublexical routes in reading and they process written stimuli sequentially (e.g., Barca et al., 2006). Additionally, sublexical processing is more evident when reading low-frequency words compared to high-frequency words — which have solid orthographic representations — regardless of orthographic complexity (Burani et al., 2006). Therefore, it has been proposed that dyslexics rely more on sublexical routes in shallow orthography (Barca et al., 2006; Zoccolotti et al., 1999). However, this reliance on sublexical processing is thought to impair their ability to develop robust lexical representations, thus hindering their progress in lexical learning and in rapid spelling recovery of familiar words (Marinelli et al., 2020). The fact that, in our study, DD individuals had similar timing in nonword-image mapping, as well as similar spelling fluency for both regular and ambiguous stimuli, may indicate inadequate integration of the novel nonwords into the lexical system as they likely rely more heavily on sublexical rather than lexical transcription processes. The findings align with the broader challenges dyslexics face in orthographic learning (Nation & Mak, 2020) and suggest that, while typical readers effectively integrate phonological, orthographic and semantic information into their lexical system, dyslexic readers continue

to experience difficulties with both regular and ambiguous stimuli.

5. Limitations

It is crucial to acknowledge the limitations of the study that may affect the interpretation and generalizability of our findings. Firstly, one important limitation of this study is the use of uppercase letters. To ensure consistency in reading and written output, we instructed our participants to use uppercase letters in handwriting and set the typing output to uppercase. We also presented nonwords in uppercase during both the learning phase and the nonword-image mapping task. This approach was intended to avoid discrepancies between the written outputs and orthographic inputs across the two conditions, which could affect the cognitive effort required to select a different allograph from what was perceived during writing. At the same time, it might have introduced effects driven by letter case rather than writing modality, potentially influencing learning outcomes. As mentioned in the methods section, we deliberately avoided asking participants to write in lowercase (script) — the letter case most consistent across different modalities — as this is not systematically taught in all schools in Italy. We acknowledge that this choice may not fully reflect ecological validity, as reading typically involves perceiving lowercase letters, typing is predominantly performed in lowercase, and handwriting in middle school is expected to be in cursive. These discrepancies may have added an extra level of difficulty in novel word learning. While the study's primary focus was on the impact of writing modality itself, the influence of letter case on performance should be considered as a possible confounding factor.

It is important to note the avoidance of cursive, which is usually the preferred letter case for our student population. The decision to avoid cursive in these tasks was not only driven by the desire for congruency between conditions but also by concerns about potential difficulties for dyslexic students. In Italy, guidelines for developmental disabilities (Ministero dell'Istruzione e del Merito, 2011) recommend starting writing education with uppercase letters and transitioning to cursive once letter formation is consolidated. Consequently, our participants might have encountered challenges with cursive writing, as confirmed by clinicians at the data collection sites. Given this, we opted for uppercase letters, as all children have learned and consolidated this letter form. Future research could address this by exploring the effects of case familiarity on learning more directly or by replicating the study using different reading and writing cases.

A key limitation of our study is the absence of a control group matched in reading age with our dyslexic participants. This prevents us from definitively determining whether the observed facilitation with typing is specific to dyslexia, or if it reflects a broader pattern of slow literacy development. It has to say that previous studies with younger participants found a superiority of handwriting (e.g., Kiefer et al., 2015; Mangen et al., 2015) or no effect of writing modality in orthographic learning (e.g., Ouellette & Tims, 2014; Suggate et al., 2023), as mentioned in the introduction.

Another limitation is the small number of repetitions of the novel words during learning. We opted to repeat each word four times to ensure that the experimental session did not exceed 50 min, roughly the duration of a school hour. While this repetition may have constrained the depth of learning, it was nevertheless effective in eliciting orthographic and semantic retention above chance levels for both groups (25 % in the nonword-image mapping task).

Lastly, our study focused on Italian-speaking participants and the generalizability of our findings to other languages may be limited. Orthographic learning processes can vary significantly across different linguistic contexts (Marinelli et al., 2020; Share, 2004; van Daal & Wass, 2017). For example, in a recent study Marinelli et al. (2020) found that children learning an orthographically inconsistent language, such as English, demonstrated superior ability in acquiring novel written words presented alongside pictures compared to children learning an

orthographically consistent language like Italian. Importantly, children were asked to spell the novel words in both learning and testing phase. According to the authors, English irregularities may promote whole-word memory storage and larger orthographic unit processing, while Italian consistent orthography relies on grapheme-phoneme conversion, which may challenge lexical representation formation. Further cross-linguistic research would be valuable in exploring whether handwriting and typing affect differently lexical learning in languages with varying orthographic consistency. This is especially relevant considering that the processing of orthographic units may differ across the two writing modalities (Cerni & Job, 2022, 2023).

6. Conclusions and implications

By elucidating the differential effects of learning modalities on writing fluency, spelling accuracy, and semantic retrieval, the study underscores the importance of considering the role of writing modalities in reinforcing the lexical system in both dyslexic and typically developed readers. Our investigation extends beyond the conventional consideration of children in primary grades, incorporating a sample of Italian middle school students to understand the effects of diverse sensorimotor writing experiences on lexical learning in students accustomed to handwriting in school but frequently engaged in typing for various daily activities, including specific school lessons, homework, and leisure pursuits. Moreover, the widespread use of keyboard-based technologies as assistive tools for students with reading and spelling difficulties (Morphy & Graham, 2012) underscores the need to comprehend the impact of typing practice on their vocabulary. This consideration is particularly relevant given that typing involves simpler motor programming but is less practiced than handwriting in educational contexts and is often not formally taught. Our findings suggest that practicing typing may help address specific challenges in integrating phonological, orthographic, and semantic information by circumventing the complex motor demands associated with handwriting. Consequently, training aimed at improving keyboard proficiency could potentially benefit reading and spelling acquisition when defecting. On the other hand, it is crucial to recognize and reflect on the difficulties dyslexic individuals face in integrating handwriting and linguistic information. Further investigations are warranted to explore strategies for enhancing this integration, to improve writing performance and orthographic learning outcomes for individuals with dyslexia.

CRedit authorship contribution statement

Tania Cerni: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Isabella Lonciari:** Resources, Project administration. **Remo Job:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Ethical statement

Ethical approval was received from the ethical committee of the University of Trento [Protocol n. 2019-041] and from the Comitato Etico Unico Regionale - CEUR FVG (the ethical committee of the Friuli Venezia Giulia Region, Study ID: 3946). The study was conducted following the ethical and legal requirements.

Funding

The present work was financially supported by the Fondazione Cassa di Risparmio di Trento e Rovereto (Caritro), Trento, Italy [Grant Number 2018.0296], and by the Promobilia Foundation, Stockholm, Sweden [Grant Number 19054]. Additional support was provided by the Italian Ministry of Health, through the contribution to the Institute for Maternal

and Child Health IRCCS Burlo Garofolo, Trieste, Italy.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to assist with language improvements and translation. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of interests

The authors report no known conflicts of interest. The authors declare that the financial support received did not influence the study's design, data collection, analysis, or interpretation of the results.

Acknowledgments

The authors express their profound gratitude to the administration and teachers of I.C. "Divisione Julia" school, and especially to Rossano Puggioni, for their invaluable support in organizing the data collection. Special thanks are also extended to Chiara Tencati (A.P.S.P. "Beato de Tschiderer", Trento, Italy) for her contribution to the initial stages of data collection. Finally, we sincerely thank the participating students and their families for their essential collaboration in this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.learninstruc.2025.102119>.

Data availability

The data that support the findings of this study are openly available in Open Science Framework at <https://osf.io/98xwe/>.

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