

## "How do spelling, handwriting speed and handwriting quality develop during primary school? Cross-classified growth curve analysis of children's writing development"

Gosse, Claire ; Parmentier, Michaël ; Van Reybroeck, Marie

### ABSTRACT

Aim. Longitudinal studies are rare in the field of writing research, and little is known about the concurrent development of the two transcription skills: spelling and handwriting. This study was designed to provide a comprehensive picture of the development and the longitudinal relations between spelling, handwriting speed and handwriting quality at the word level. Method. Over a period of three years (coh1: Grades 2–4; coh2: Grades 3–5), 117 French-speaking children were assessed on a single-word dictation task. At each testing time, measures of spelling accuracy, handwriting speed and handwriting quality were collected on 40 words. Words varied in both orthographic and graphic complexity, making it possible to investigate the influence of these levels of complexity on transcription abilities. Results. Linear growth analyses using cross-classified Bayesian structural equation modelling revealed that spelling and speed continued to improve until Grade 5, while handwriting quality reached an early plateau in Grade 2. In the younger cohort, graphic complexity had a significant influence on the pace of development of handwriting speed and on spelling and handwriting quality performance in Grade 2. In the older cohort, a positive relation between spelling and speed and a negative relation between handwriting speed and handwriting quality were found, indicating that fast handwriting is associated with high spelling ability and that fast handwriting is detrimental to handwriting quality. By providing a better understanding of writing development, this study yields innovativ...

### CITE THIS VERSION

Gosse, Claire ; Parmentier, Michaël ; Van Reybroeck, Marie. *How do spelling, handwriting speed and handwriting quality develop during primary school? Cross-classified growth curve analysis of children's writing development*. In: *Frontiers in Psychology*, (2021) <http://hdl.handle.net/2078.1/248932> -- DOI : 10.3389/fpsyg.2021.685681

Le dépôt institutionnel DIAL est destiné au dépôt et à la diffusion de documents scientifiques émanant des membres de l'UCLouvain. Toute utilisation de ce document à des fins lucratives ou commerciales est strictement interdite. L'utilisateur s'engage à respecter les droits d'auteur liés à ce document, principalement le droit à l'intégrité de l'œuvre et le droit à la paternité. La politique complète de copyright est disponible sur la page [Copyright policy](#)

DIAL is an institutional repository for the deposit and dissemination of scientific documents from UCLouvain members. Usage of this document for profit or commercial purposes is strictly prohibited. User agrees to respect copyright about this document, mainly text integrity and source mention. Full content of copyright policy is available at [Copyright policy](#)

# How do spelling, handwriting speed and handwriting quality develop during primary school? Cross-classified growth curve analysis of children's writing development

Claire Gosse<sup>1\*</sup>, Michael Parmentier<sup>1</sup>, Marie Van Reybroeck<sup>1</sup>

<sup>1</sup>Catholic University of Louvain, Belgium

*Submitted to Journal:*  
Frontiers in Psychology

*Specialty Section:*  
Educational Psychology

*Article type:*  
Original Research Article

*Manuscript ID:*  
685681

*Received on:*  
25 Mar 2021

*Revised on:*  
18 Jun 2021

*Journal website link:*  
[www.frontiersin.org](http://www.frontiersin.org)

---

### *Conflict of interest statement*

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

### *Author contribution statement*

CG developed the research questions, designed the experiment, performed the experiment, scored the tasks, interpreted the results, drafted and revised the manuscript. MP analysed the data, discussed data interpretations, wrote the results section and revised the manuscript. MVR developed the research questions, designed the experiment, discussed data interpretations, revised the manuscript.

### *Keywords*

Writing development, spelling, Handwriting speed, Handwriting legibility, longitudinal cross-classified Bayesian structural equation modelling

### *Abstract*

Word count: 256

*review*

**Aim.** Longitudinal studies are rare in the field of writing research, and little is known about the concurrent development of the two transcription skills: spelling and handwriting. This study was designed to provide a comprehensive picture of the development and the longitudinal relations between spelling, handwriting speed and legibility at the word level. **Method.** Over a period of three years (coh1: Grades 2-4; coh2: Grades 3-5), 117 French-speaking children were assessed on a single-word dictation task. At each testing time, measures of spelling accuracy, handwriting speed and handwriting quality were collected on 40 words. Words varied in both orthographic and graphic complexity, making it possible to investigate the influence of these levels of complexity on transcription abilities. **Results.** Linear growth analyses using cross-classified Bayesian structural equation modelling revealed that spelling and speed continued to improve until Grade 5, while handwriting quality reached an early plateau in Grade 2. In the younger cohort, graphic complexity had a significant influence on the pace of development of handwriting speed and on spelling and handwriting quality performance in Grade 2. In the older cohort, a positive relation between spelling and speed and a negative relation between handwriting speed and handwriting quality were found, indicating that fast handwriting is associated with high spelling ability and that fast handwriting is detrimental to legibility. By providing a better understanding of writing development, this study yields innovative findings not only regarding the development of transcription skills but also regarding how spelling, handwriting speed and handwriting quality can influence each other's performance throughout primary school.

### *Contribution to the field*

This study aimed to provide a comprehensive picture of the concurrent development of spelling and handwriting. In this longitudinal experiment, we directly addressed the relationships between spelling and handwriting, to shed light on how they influence each other during writing acquisition. Moreover, we considered both components of handwriting: legibility and speed, which has rarely been done in past research. We conducted robust statistical analyses, namely cross-classified Bayesian structural equation modelling in order to fully account for the nesting of the longitudinal data within both children and words. Our findings revealed that young writers spell less accurately words that are graphically complex, that children with better spelling abilities have faster handwriting, and that Handwriting speed and handwriting legibility are negatively associated. To the best of our knowledge, no previous study had ever collected longitudinal data on a large sample of children on both spelling and handwriting abilities. Our findings are very relevant to the field of writing research, and they open up interesting avenues for instructional practices.

### *Funding statement*

This study benefitted from financial support from Fondation Louvain (Belgium) and Fonds de la Recherche Scientifique - FNRS (Belgium; Grant 1.A.690.18F)

*Ethics statements*

*Studies involving animal subjects*

Generated Statement: No animal studies are presented in this manuscript.

*Studies involving human subjects*

Generated Statement: The studies involving human participants were reviewed and approved by Ethical Committee of the Psychological Sciences Research Institute . Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

*Inclusion of identifiable human data*

Generated Statement: No potentially identifiable human images or data is presented in this study.

In review

*Data availability statement*

Generated Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

In review

1 **How do spelling, handwriting speed and handwriting quality develop during primary**  
2 **school?**

3 **Cross-classified growth curve analysis of children's writing development**  
4

5 **Abstract**

6 **Aim.** Longitudinal studies are rare in the field of writing research, and little is known about  
7 the concurrent development of the two transcription skills: spelling and handwriting. This  
8 study was designed to provide a comprehensive picture of the development and the  
9 longitudinal relations between spelling, handwriting speed and **handwriting quality** at the  
10 word level. **Method.** Over a period of three years (coh1: Grades 2–4; coh2: Grades 3–5), 117  
11 French-speaking children were assessed on a single-word dictation task. At each testing time,  
12 measures of spelling accuracy, handwriting speed and handwriting quality were collected on  
13 40 words. Words varied in both orthographic and graphic complexity, making it possible to  
14 investigate the influence of these levels of complexity on transcription abilities. **Results.**  
15 Linear growth analyses using cross-classified Bayesian structural equation modelling revealed  
16 that spelling and speed continued to improve until Grade 5, while handwriting quality reached  
17 an early plateau in Grade 2. In the younger cohort, graphic complexity had a significant  
18 influence on the pace of development of handwriting speed and on spelling and handwriting  
19 quality performance in Grade 2. In the older cohort, a positive relation between spelling and  
20 speed and a negative relation between handwriting speed and handwriting quality were found,  
21 indicating that fast handwriting is associated with high spelling ability and that fast  
22 handwriting is detrimental to handwriting quality. By providing a better understanding of  
23 writing development, this study yields innovative findings not only regarding the  
24 development of transcription skills but also regarding how spelling, handwriting speed and  
25 handwriting quality can influence each other's performance throughout primary school.

26 *Keywords: writing development, spelling, handwriting speed, handwriting legibility,*  
27 *longitudinal cross-classified Bayesian structural equation modelling*

28

29

1

## 1. Introduction

2 At the beginning of formal education, learning to write occupies a major place in the  
3 classroom. Writing is a complex ability that takes time to develop, involving a wide range of  
4 cognitive, psychomotor and perceptual-motor processes (Feder & Majnemer, 2007; Van  
5 Galen, 1991). Learning to write represents a long-lasting challenge for children, which starts  
6 with the acquisition of the foundations of writing: spelling and handwriting, the two  
7 transcription skills. These transcription skills originate from different domains, with spelling  
8 being a language-based component and handwriting a motor-based ability. Van Galen's  
9 (1991) reference theory of writing represented orthographic and graphomotor skills as  
10 separate processes, occurring one after the other in a discrete manner. Since then, studies have  
11 demonstrated that spelling and graphomotor processes have influenced each other during the  
12 course of writing, challenging this vision of independent processes (Authors, 2020b; Kandel  
13 & Perret, 2015; Palmis et al., 2019). However, little is known about the concurrent  
14 development of transcription skills, and our understanding of how spelling and handwriting  
15 influence each other is limited (Caravolas et al., 2020). Even though the current literature  
16 contains studies focused on either children's spelling or handwriting, collecting data that  
17 consider both transcription skills together is necessary to understand their relationship.  
18 Moreover, although it is a major aspect of handwriting, legibility has only rarely been  
19 investigated in typically developing children (Caravolas et al., 2020; Authors, 2018). Indeed,  
20 the great majority of studies on handwriting reported results based on the dynamic parameters  
21 of handwriting (i.e., speed, pausing). Finally, longitudinal designs are very rare in the field of  
22 writing development (Abbott et al., 2010; Barnett et al., 2019; Bosga-Stork et al., 2016),  
23 which constitutes a gap in the current literature.

24 The present study is a longitudinal study aimed at providing a comprehensive picture  
25 of the concurrent development of transcription skills at the word level. For the first time,  
26 spelling accuracy, handwriting speed and handwriting quality were studied simultaneously in  
27 a single word writing context. By taking into consideration both transcription skills, this study  
28 was designed to address the question of the development of each skill and how they relate to  
29 each other at different ages. To this end, over a period of three years, 117 French-speaking  
30 children with no learning difficulties were assessed on a single-word dictation task. At each  
31 testing time, measures of spelling accuracy, handwriting speed and handwriting quality were  
32 collected for each word. The words used in the dictation task varied in orthographic and  
33 graphic levels of complexity in order to assess their influence on transcription abilities. Cross-  
34 classified Bayesian structural equation modelling was used to investigate children's  
35 concurrent development of spelling and handwriting, allowing the integration of both the  
36 psycholinguistic (i.e., orthographic and graphic levels of complexity at the word level) and  
37 longitudinal approaches.

### 38 1.1. The Transcription Skills

#### 39 1.1.1. Spelling Accuracy

40 In all languages, becoming an accurate speller takes several years (Treiman, 2017). At

1 the word-level, children begin spelling acquisition by relying on phonological processes,  
 2 allowing to build the words by applying phoneme to grapheme correspondences. However,  
 3 correctly applying these correspondences is not sufficient to master word spelling, as some  
 4 words have irregular spelling, i.e., a low degree of consistency between phonemes and  
 5 graphemes (Treiman, 2017). This is especially true in languages like English and French,  
 6 often referred as opaque orthographic systems (Salas & Caravolas, 2019).

7 In French, the language of the present study, over half of the words contain phonemes  
 8 that can be spelled in different ways (Ziegler et al., 1996). For example, there are several  
 9 phonologically correct ways of spelling the phoneme [ɛ̃], using the graphemes *in*, *ain* and *ein*  
 10 like in *vin* (wine), *main* (hand) and *plein* (full). French also contains words with inaudible  
 11 letters (Casalis et al., 2011; Sénéchal, 2000), like the final silent letters in *lait* (milk) and *bois*  
 12 (wood). Research conducted on the morphological structure of words have revealed that  
 13 children use information about morphemes to choose among several possibilities of plausible  
 14 spellings (Deacon & Bryant, 2006). For example, in the case of the nouns *bois* (wood) and  
 15 *milk* (lait), clues regarding the silent letters *s* and *t* can be provided using the derived  
 16 adjectives *boisé* (wooded) or *laiteux* (milky). Children can also use contextual information  
 17 that they learn implicitly to choose between several plausible spellings, as they are sensitive  
 18 from a young age to the frequency of orthographic patterns (Hayes et al., 2006; Pacton et al.,  
 19 2001). In other words, children can take spelling decisions by selecting the most frequent  
 20 orthographic patterns among several plausible spellings (e.g., in French, most of the words  
 21 starting with the sound [ap] are spelled with a double consonant *pp* like in *apprendre* (learn),  
 22 *appeler* (call), *apparaître* (appear)).

23 Regarding the pace of spelling development, longitudinal data collection are rare, and  
 24 results vary depending on the language at stake, as the rate of spelling development depends  
 25 on the level of orthographic consistency (Salas & Caravolas, 2019). A longitudinal study  
 26 conducted in French from Grade 1 to Grade 4 revealed that irregular words were still being  
 27 produced significantly less accurately than regular words at the end of Grade 4 (Sprenger-  
 28 Charolles et al., 2003). These longitudinal data indicated that the development of spelling was  
 29 still ongoing at the end of Grade 4. The importance of the regularity parameter for spelling  
 30 development in French has been highlighted in other psycholinguistic experiments (Martinet  
 31 et al., 2004; Tainturier & Rapp, 2001). For regular words, i.e., those with a high degree of  
 32 consistency, spelling is easier and therefore more accurate than it is for irregular words, and  
 33 this effect is long lasting. Throughout the literacy experience and word-writing practice,  
 34 children progressively access words' spelling forms quicker, as they can use their  
 35 orthographic lexicon in long-term memory (Sprenger-Charolles et al., 1998).

### 36 **1.1.2. Handwriting Ability**

37 Handwriting is a psychomotor ability defined by two outcomes: speed and legibility,  
 38 also referred as handwriting quality (Graham et al., 2006). The handwriting style used by  
 39 children throughout the world depends on their national education context. In alphabetic  
 40 contexts, we find two main handwriting styles: cursive vs. script (e.g., respectively *handwriting*



1 vs. *handwriting*). Cursive handwriting implies continuous graphomotor movement, while script  
2 handwriting, typical of English-speaking countries, requires pausing between each letter.  
3 Moreover, the visual characteristics of letters vary (Bara & Morin, 2013; Morin et al., 2012),  
4 and the number of strokes composing each letter can also differ depending on the handwriting  
5 style (e.g., cursive *j* has more strokes than script *j*).

6 Handwriting speed has been the centre of many recent experiments in both cursive  
7 (e.g., Alamargot et al., 2020; Authors, 2020) and script styles (e.g., Sumner et al, 2014), with  
8 digital tablets providing data recordings of the dynamics of handwriting (e.g., pen pressure,  
9 speed, writing duration). In contrast, there is a lack of objective and sensitive measures of  
10 legibility (Barnett et al., 2018), which presumably explains why it has been overlooked  
11 compared to speed. However, it is essential to take an interest in legibility since poor  
12 handwriting can have far-reaching consequences for children's self-esteem and academic  
13 achievement (Feder & Majnemer, 2007; Medwell & Wray, 2007). The few studies focusing  
14 on legibility used criteria that are commonly related to letter formation and to spatial  
15 organisation within and between words (e.g., unusual letter shapes, size fluctuation, bad letter  
16 alignment, abnormal space between letters; Caravolas et al., 2020; Graham et al., 2006). Such  
17 criteria allow identifying children who have graphomotor difficulties, leading to illegible  
18 handwriting like in the case of developmental coordination disorder or, to a lesser extent,  
19 dyslexia (Di Brina et al., 2018; Downing & Caravolas, 2020; Prunty & Barnett, 2017).  
20 However, handwriting has never been investigated with such precise legibility criteria in  
21 typically developing children, to measure the quality of their handwriting.

22 Regarding handwriting developmental paths, few studies have examined the growth in  
23 handwriting speed and legibility. To the best of our knowledge, only one experiment by  
24 Karlsdottir and Stefansson (2002) has collected longitudinal data covering several school  
25 years (Grade 1 to Grade 5). Handwriting speed and legibility were assessed in over 400  
26 Norwegian children. The results revealed that children's handwriting quality increased rapidly  
27 during first grade, with children reaching a plateau at the end of Grade 1. In contrast, the  
28 speed of handwriting had a continuous and linear developmental pattern. These results  
29 confirmed in part a large cross-sectional experiment conducted by Graham et al. (1998)  
30 covering Grades 1–9. Their findings demonstrated a plateau in legibility occurring in the  
31 middle grades, not as early as in Karlsdottir and Stefansson's (2002) study, but continuing to  
32 improve until the later grades. Moreover, Graham et al. (1998) reported that correlations  
33 between legibility and speed were weak, which supported the idea that the two components of  
34 handwriting have different developmental patterns.

35 While the psycholinguistic characteristics that determine orthographic complexity are  
36 documented (i.e., word regularity), little is known about the parameters that influence the  
37 graphic complexity of words. Recent findings have demonstrated that words vary in levels of  
38 graphic complexity, depending on the fine graphomotor skills and motor control abilities  
39 implied by the pen stroke trajectory. Specifically, tracing pieces that contain abrupt changes  
40 in the pen stroke trajectory (e.g., the angle in *r*) is more difficult than tracing curvy segments  
41 (e.g., *c*; Authors, 2018). To the best of our knowledge, no study has ever investigated the

1 development of handwriting by taking into account the different levels of graphic complexity  
2 required by handwriting.

### 3 ***1.1.3. Spelling and Handwriting Instruction in the Current Context***

4 Handwriting and spelling instruction vary greatly from one country to another,  
5 depending on the handwriting style taught and the language at stake. The current study was  
6 conducted in a French-speaking context in Belgium. With regard to handwriting instruction,  
7 block letters are taught before entering primary school, at the end of Kindergarten. Once in  
8 primary school, children all use cursive style exclusively, as script style is never taught in  
9 French-speaking Belgian schools. Handwriting instruction occurs during first grade, and  
10 according to the national school curriculum, children by the end of Grade 2 are all expected to  
11 produce legible handwriting and to master organisation and neatness of their sheets of paper.  
12 In contrast, spelling instruction in French-speaking Belgium remains the focus of teachers  
13 throughout primary school. Typically, children start in Grade 1 by learning the  
14 correspondences between phonemes and graphemes, consisting in single letter writing  
15 followed by syllable writing. Later, teachers use lists of words that contain similar spelling  
16 patterns and progressively increase difficulty, going from highly regular words to irregular  
17 words. Spelling instruction also involves teaching contextual spelling rules and morphological  
18 principles.

## 19 **1.2. Relationship Between the Two Transcription Skills**

20 The model of writing by Van Galen (1991) represents spelling and handwriting as  
21 independent processes occurring one after the other. However, the literature contains evidence  
22 of interactions between spelling and handwriting processes during the course of writing  
23 (Caravolas et al., 2020). Current knowledge regarding the interactions between spelling and  
24 handwriting arises from studies that can be classified into two groups. The first group of  
25 experiments contained studies related to the capacity theory of writing (McCutchen, 1996)  
26 framework, which contributed to highlighting the crucial role of handwriting automatisisation  
27 in the development of higher-level writing processes. The second group is composed of  
28 psycholinguistic experiments, in which the manipulation of words' characteristics and  
29 complexity (either orthographic or graphic) was used to shed light on their impact on spelling  
30 and handwriting performances.

### 31 ***1.2.1. The Limited Capacity Theory of Writing***

32 According to McCutchen's (1996) capacity theory of writing, the lower processes of  
33 writing must be automatised to allow higher-level processes to develop. At the beginning of  
34 writing instruction, the movements necessary for letter formation are under voluntary control,  
35 requiring a large proportion of children's cognitive resources (Jones & Christensen, 1999).  
36 Throughout their experience, children progressively automate their handwriting movements,  
37 which lightens cognitive constraints and frees up resources for other processes (Chartrel &  
38 Vinter, 2004; Graham et al., 1998; Overvelde & Hulstijn, 2011). The positive key role played  
39 by handwriting automatisisation has been demonstrated for various processes of writing either

1 at the text level on composition quality (Alves & Limpo, 2015; Medwell & Wray, 2007) or at  
2 the word level on spelling accuracy (Abbott et al., 2010; Pontart et al., 2013). However, there  
3 is no consensus about the age at which this automatisisation of handwriting occurs, with data  
4 suggesting it would already occur at the end of Grade 1 (Overvelde & Hulstijn, 2011) or after  
5 Grade 7 (Alves & Limpo, 2015). As already mentioned above, the way handwriting is taught  
6 varies greatly across countries (i.e., script or cursive only or both). This variability may be  
7 one plausible explanation of the difficulty of reaching a consensus regarding the age at which  
8 handwriting is automatic.

### 9 *1.2.2 Psycholinguistic Approach in Writing Research*

10 Researchers who have adopted a psycholinguistic approach have manipulated the  
11 attributes of the words composing the experimental writing tasks (e.g., copying regular vs.  
12 irregular words in Kandel & Perret, 2015) to assess their impact on writing performance. Such  
13 experiments have led to highly informative findings regarding the relationship between the  
14 two transcription skills. Studies conducted in French have revealed that words' orthographic  
15 characteristics, especially regularity, influenced handwriting fluency in university students  
16 (Delattre et al., 2006) and in children from 8 to 10 years old (Kandel & Perret, 2015). The  
17 impact of orthographic complexity on handwriting execution has been demonstrated in adults  
18 by neuroimaging evidence (Palmis et al., 2019). The opposite direction of the relationship has  
19 also been investigated, revealing that the graphomotor demand was negatively related to  
20 grammatical spelling performance in French (Authors, 2009). Recently, a study conducted in  
21 children with and without dyslexia reported evidence of the negative impact of word graphic  
22 complexity on spelling accuracy in a sample of typically developing children (Authors,  
23 2020b). More precisely, the authors revealed that words that contained graphically complex  
24 segments (i.e., abrupt changes of pen stroke trajectory induced by the presence of letters  
25 containing angles like the letters *z* and *l*), based on the index of graphic complexity developed  
26 in Authors, 2018, were produced with more spelling errors than graphically simple words  
27 (i.e., words that are mostly composed of curvy segments like the letters *e* and *c*). Taken  
28 together, these findings have demonstrated that the orthographic and graphic sides of writing  
29 influence each other. However, no experiment has ever measured the influence of both  
30 orthographic and graphic features of words within the same writing task.

31 Finally, a developmental approach can be found in the experiment by Bosga-Stork et  
32 al. (2016) conducted with 30 Dutch children. Besides demonstrating children' handwriting,  
33 spelling, and motor skill increasing development from Grade 1 to Grade 3, their findings  
34 demonstrated that handwriting speed was positively related to spelling accuracy in Grades 1  
35 and 2 and that this correlation was no longer significant in Grade 3. Despite providing  
36 longitudinal evidence for the development of handwriting and spelling, their analysis of the  
37 relations between the two components were cross-sectional in nature. Their analysis thus  
38 failed to properly assess how handwriting and spelling co-develop and their relationships over  
39 time. For this reason and because of the small sample size ( $N = 30$ ), this study was qualified  
40 by the authors themselves as exploratory. Moreover, this experiment did not take into  
41 consideration the **quality** component of handwriting.

1 To conclude, while the spelling side of writing is a well-documented ability, little is  
2 known about the development of handwriting. Even if spelling and handwriting abilities  
3 originate from separate cognitive processes, the studies presented in the above introduction  
4 section provided evidence of their interaction during the course of writing. Indeed,  
5 psycholinguistic studies revealed a significant influence of the orthographic characteristics of  
6 words on handwriting outcomes (e.g., Kandel & Perret, 2015). However, these  
7 psycholinguistic studies did not address the issue of the development of spelling and  
8 handwriting. The one experiment that used a developmental approach to investigate the  
9 concurrent development of spelling and handwriting were of a correlational nature (Bosga-  
10 Stork et al., 2016). Moreover, the assessment of handwriting was limited to measures of  
11 speed, while **handwriting quality** has never been investigated in relation to spelling. To the  
12 best of our knowledge, the concurrent development of spelling, handwriting speed and **quality**  
13 has never been investigated with a longitudinal approach. Such data would be a meaningful  
14 contribution to the field of research by providing for the first time a comprehensive picture of  
15 word writing development.

16

## 2. The Present Study

17 The purpose of this study was to better understand the typical development at the  
18 word-level of spelling, handwriting speed and handwriting quality throughout primary school.  
19 The current study involved longitudinal data collected from 117 French-speaking children,  
20 who used cursive handwriting style only. Standardised control measures of general cognitive  
21 and literacy abilities were collected to ensure that all children were typically developing. The  
22 experimental task was a single word dictation task that children performed once a year for a  
23 period of three consecutive years. Children's spelling accuracy, handwriting speed and  
24 handwriting quality were assessed at each measurement time. Through the manipulation of  
25 both orthographic and graphic levels of complexity of words, this study investigates how the  
26 orthographic and graphic sides of writing influence the development of the transcription  
27 abilities. Spelling and handwriting (both quality and speed) have never been considered in  
28 relation to the orthographic and graphic features of words within the same experiment, even  
29 more so using longitudinal data collection. The impact of word levels of orthographic and  
30 graphic complexity on spelling and handwriting abilities was assessed. **Cross-classified**  
31 **Bayesian structural equation modelling (CC-BSEM) was used in the present study to account**  
32 **for (1) the cross-nested structure of the data within children and words at the same time and**  
33 **(2) the repeated-measures longitudinal design and (3) the concurrent development of spelling,**  
34 **handwriting speed and quality. While mixed effects models have been widely used to study**  
35 **cross-classified data structures (Judd et al., 2012; Baayen et al., 2008), the CC-BSEM**  
36 **approach allows greater flexibility in adopting a multivariate structural equation modelling**  
37 **framework (Wickham et al., 2021).** To the best of our knowledge, the present study is the first  
38 to adopt a CC-BSEM approach to address the question of the developing relationship between  
39 spelling, handwriting speed and handwriting quality. One of the main advantages of our  
40 approach is that it allowed us to investigate, at the word level, the typical development of  
41 spelling, handwriting speed and quality while, simultaneously, examine how their  
42 development is intertwined over time.

1 Participants were from two cohorts with a one-year difference (coh1: Grade 2 to Grade  
2 4; coh2: Grade 3 to Grade 5), implying different degrees of handwriting automatisa-  
3 tion. Indeed, coh1 children were in Grade 2 at the start of the study, having received only a year  
4 and a half of handwriting instruction, while coh2 children were in Grade 3, having received  
5 an additional full year of handwriting experience. Therefore, the level of graphomotor  
6 automatisa- tion between the two cohorts was different, being lower in coh1 than in coh2.

7 The present study addressed the three following research questions:

8 (i) How do spelling, handwriting speed and handwriting quality develop at the word  
9 level?

10 Since the present study was conducted in French, an opaque orthography, we expected  
11 spelling accuracy to continue growing (Sprenger-Charolles et al., 2003) until the end of the  
12 longitudinal study for both cohorts. In line with past research, the same prediction applies for  
13 handwriting speed (Graham et al., 1998), for which we expected a linear and continuous  
14 improvement in both cohorts. Regarding handwriting quality, findings in past research have  
15 observed an “early plateau” in the development of ability (Graham et al., 1998; Karlsdottir &  
16 Stefansson, 2002). However, these findings were contradictory about the earliness of this  
17 plateau during primary school. By drawing the development of handwriting quality using  
18 precise aesthetic criteria in two cohorts of different ages (coh1: Grades 2–4; coh2: Grades 3–  
19 5), the present study could help clarify the age at which this plateau is reached.

20 (ii) How do the orthographic complexity and graphic complexity of words influence  
21 children’s spelling accuracy, handwriting speed and handwriting quality?

22 With regard to orthographic complexity, past literature has demonstrated its long-  
23 lasting influence (i.e., irregular words compared to regular words) on spelling accuracy  
24 (Sprenger-Charolles et al., 2003) and on handwriting production (in children, Kandel &  
25 Perret, 2015; in adults, Palmis et al., 2019). Therefore, we expected the influence of  
26 orthographic complexity to be present at all measurement times in both cohorts.  
27 Orthographically difficult words should lead to less accurate spelling, slower handwriting and  
28 poorer handwriting quality than orthographically simple words.

29 With regard to graphic complexity, past research has demonstrated that the  
30 graphomotor cost of handwriting could impact spelling accuracy (Authors, 2009),  
31 handwriting speed and handwriting quality (Authors, 2018). Because children in the younger  
32 cohort (coh1) had less automatised handwriting than coh2 children at the start of the study, we  
33 assumed that the impact of graphic complexity would be greater in coh1 than in coh2. Young  
34 children (coh1) should produce less accurate spelling, slower handwriting and poorer  
35 handwriting quality when words are graphically difficult than older children (coh2).

36 (iii) How are spelling, handwriting speed and handwriting quality related to each other  
37 throughout development?

1 Overall, past research has demonstrated close associations between spelling ability and  
2 handwriting speed. In line with previous findings (Bosga-Stork et al., 2016), we expected this  
3 relationship to be stronger at the beginning of writing development and to decrease  
4 throughout primary school thanks to handwriting automatisation.

5 The development of handwriting quality has, to the best of our knowledge, never been  
6 investigated in association with spelling. Therefore, the hypotheses proposed in the current  
7 study are exploratory. First of all, in line with a recent experiment conducted by Arfé et al.  
8 (2020), we expect the relationship between handwriting quality and spelling to be less  
9 important than the relationship between handwriting speed and spelling accuracy. Moreover,  
10 in line with the capacity theory of writing (McCutchen, 1996), we expect the relationship  
11 between spelling and handwriting quality to be stronger at the beginning of the study, before  
12 handwriting is automatised. Indeed, before handwriting automatisation, children need to  
13 allocate more cognitive resources to handwriting at the expense of spelling accuracy.  
14 Therefore, we assumed that the relationship between handwriting quality and spelling would  
15 be greater in coh1 (Grades 2–4) than in coh2 (Grades 3–5). This relationship should gradually  
16 decline, reflecting progressive automatisation of handwriting.

17 Given the evidence of a lack of association between the two components of  
18 handwriting among typically developing children (Graham et al., 1998), we expected no  
19 relation between handwriting speed and handwriting quality throughout development in either  
20 cohort.

### 21 3. Method

#### 22 3.1. Participants

23 Children from eight classes from two French-speaking schools in Belgium participated  
24 in the study ( $N = 136$ ). In the present national context, cursive handwriting was the only style  
25 used at school, implying that all participants had been taught handwriting in a cursive style  
26 from the beginning of primary school. Depending on their grade at the beginning of the study,  
27 the children belonged to two different cohorts, with a year of difference between the two.  
28 Coh1 children began the study in Grade 2 and continued each year until Grade 4, and coh2  
29 began in Grade 3 and continued each year until Grade 5. The ethical commission of the  
30 research institute (Anonymous) of the main experimenter's institution approved the study  
31 (reference: Anonymous). The headmasters and the teachers voluntarily took part in this study,  
32 and parents' active consent was required for their child's participation. Parental consent was  
33 renewed the month preceding each testing time. Data were collected in 2017 (T1: coh1 in G2;  
34 coh2 in G3), 2018 (T2: coh1 in G3; coh2 in G4) and 2019 (T3: coh1 in G4; coh2 in G5). No  
35 selection criteria were used at the beginning of the study, but 19 children were excluded from  
36 the analysis based on the following criteria: (i) performance more than 2 SD below age-  
37 appropriate norms on at least two standardised tests ( $n = 10$ ); (ii) French as second language ( $n$   
38 = 6); (iii) drop out due to moving to new schools during data collection ( $n = 3$ ).

1 Therefore, the present sample was composed of 117 typically developing children  
 2 with average nonverbal cognitive ability (Matrices subset of the WISC-IV, Wechsler, 2005)  
 3 and receptive vocabulary ability (EVIP designation task, Dunn et al., 1993). Details regarding  
 4 participants' characteristics at each measurement time are presented in Table 1. **Group**  
 5 **comparisons were conducted on all control measures at T1 (coh1: Grade 2; coh2: Grade3)**  
 6 **based on z-scores**. The independent samples t test analyses revealed that both cohorts had  
 7 equivalent scores in word-reading ( $t(110) = -1.59; p = .115$ ), handwriting quality ( $t(110) =$   
 8  $1.35; p = .179$ ) and nonverbal IQ ( $t(110) = -1.39; p = .160$ ). In contrast, the two cohorts  
 9 differed on the following scores: word-spelling accuracy ( $t(110) = -3.07; p = .003$ );  
 10 handwriting speed ( $t(110) = -2.85; p = .005$ ) and receptive vocabulary ( $t(110) = -2.32; p =$   
 11  $.022$ )

## 12 **3.2. Materials**

13 The experimental task designed for the present study was a single-word dictation task.  
 14 To complete the task, each child was given a digital tablet and a digital pen (Wacom Intuos  
 15 Pro Medium and Wacom Inking Pen). The tablet size was 380 x 251 x 12 mm, with an active  
 16 area of 224 x 140 mm. The single-word dictation task was composed of 40 words and  
 17 remained the same at the three testing times. The words were selected according to their  
 18 levels of orthographic complexity and graphic complexity.

### 19 **3.2.1. Orthographic Complexity (O-simple and O-difficult)**

20 The orthographic level of complexity refers to the spelling demand of words. To  
 21 determine the words' level of orthographic complexity, we took into account word regularity  
 22 and word success rate for children in Grade 2 in the French database EOLE (Echelle  
 23 d'acquisition en orthographe lexicale [lexical spelling acquisition scale]; Pothier & Pothier,  
 24 2003). Regular words with a high success rate ( $> 75\%$  in EOLE for Grade 2) were selected  
 25 for the lists of orthographically simple words (O-simple). In contrast, words with complex or  
 26 irregular phoneme-grapheme correspondences and with a lower success rate ( $< 50\%$  in EOLE  
 27 for Grade 2) were selected for the lists of orthographically difficult words (O-difficult).

### 28 **3.2.2. Graphic Complexity (G-simple and G-difficult)**

29 The graphic level of complexity refers to the graphomotor demands required in  
 30 handwriting words. For example, words that include abrupt changes in the pen stroke  
 31 trajectory are more complex than words containing curvy segments. This information came  
 32 from a previous experiment conducted by Authors (2018), which determined how these  
 33 graphic characteristics impacted children's handwriting speed and **quality**. Each graphic  
 34 characteristic was quantified in terms of level of complexity, which led to an index giving the  
 35 value of graphic complexity for each word. To determine the reference values for low and  
 36 high levels of graphic complexity (G-simple vs. G-difficult), the index was applied to a  
 37 complete French lexical database (LEXIQUE, New et al., 2004). Then, the 25 and 75  
 38 percentiles of the index were used as thresholds for the G-simple (index = 15.6) and G-  
 39 difficult (index = 19.4) conditions.

1 The four lists were composed of simple or complex words on both the orthographic  
2 and graphic dimensions (O-simple, G-simple, O-difficult, and G-difficult). They were  
3 matched on the number of letters, digram frequency, success rate and graphic complexity  
4 index. Table 2 presents the four list characteristics and the ten words composing each list.

### 5 **3.3. Measures**

6 In the present study, children were administered several control measures as well as a  
7 single-word dictation experimental task. The control measures were used to provide  
8 information about the participants' written language skills. The experimental task was  
9 designed to answer the research questions.

#### 10 **3.3.1. Experimental Measures**

11 **3.3.1.1. Spelling Accuracy in the Experimental Task.** Children were given one point  
12 for each word correctly spelled and a score of 0 in the case of a spelling error. The internal  
13 reliability in the current sample given by Cronbach's alpha is .87. The categorical nature of  
14 spelling accuracy was taken into account in the subsequent statistical analyses.

15 **3.3.1.2. Handwriting Speed in the Experimental Task.** Each word's production time  
16 was directly extracted from the tablets, measured in milliseconds, giving a value for  
17 handwriting speed. The recording started at the beginning of each word's pen stroke until the  
18 end of the word. The pauses inside the words and in air phases (i.e., pen lifts) were not taken  
19 into consideration. **The values for speed refer to the distance covered while the pen was on the**  
20 **sheet of paper expressed in centimetres per second (cm/s).** A low value refers to slow  
21 handwriting, whereas high values refer to fast handwriting execution.

22 **3.3.1.3. Handwriting Quality in the Experimental Task.** Scoring of handwriting  
23 quality was inspired by the BHK scale (Charles et al., 2004). Five aesthetic criteria, selected  
24 because they suited the single-word context, were taken into account for handwriting **quality**.  
25 They all refer to a type of graphical error. Each word was assessed in a binary way, with a  
26 score of 1 assigned in the presence of a graphic abnormality and 0 being the score for the  
27 expected handwriting performance. The presence of one of the following abnormal elements  
28 was systematically noted: (1) distortion of a letter, manifesting as an abnormal letter form; (2)  
29 inconsistent letter size, referring to a situation where there is an abnormal variation in the  
30 letter size within the same word; (3) inconsistent relative height of letters, meaning that small  
31 letters (e.g., *a*, *i*, *s*) are produced at the same height as tall or tail letters (e.g., *y*, *t*, *h*) and vice  
32 versa; (4) correction of letter forms, noticeable by the presence of a graphic correction on  
33 paper; and (5) bad letter alignment within the word, when the horizontality of the handwriting  
34 is violated. For descriptive purposes, a total score per word was computed by adding the score  
35 for each criterion, leading to a maximum score of 5 per written word. For handwriting **quality**,  
36 high scores refer to poor handwriting, while lower scores refer to better **quality**. Cronbach's  
37 alphas were calculated within the present sample for each aesthetic criterion separately, and  
38 they revealed very high internal reliability: .92 for distortion of letters, .90 for inconsistent  
39 letter size, .85 for inconsistent relative height of letters, .80 for correction of letter forms, and



1 .94 for bad letter alignment. For analytical purposes, the categorical nature of these five  
 2 criteria was taken into account in the subsequent statistical analyses and construed as  
 3 observed categorical indicators of a latent variable in all subsequent models.

#### 4 **3.3.2. Standardised Control Measures**

5 **3.3.2.1. Spelling Accuracy.** Spelling ability was assessed with a sentence dictation  
 6 task (Chronosdictées, Beneath et al., 2006). Children's scores were compared to the norms for  
 7 their grade on phonological spelling, lexical spelling and grammatical spelling as well as their  
 8 total score. The present experimental results will indicate only the children's total score.

9 **3.3.2.2. Handwriting Speed in the Copying Task.** Participants' handwriting speed  
 10 was assessed with a standardised text copying task in the limited time of five minutes (BHK,  
 11 [Concise evaluation scale for children handwriting]; Charles et al., 2004). The number of  
 12 letters correctly copied was scored, which is an indicator of handwriting speed.

13 **3.3.2.3. Handwriting Quality in the Copying Task.** The quality of the handwriting  
 14 was also assessed with the standardised test BHK (Charles et al., 2004). Each sentence was  
 15 scored according to aesthetic criteria. Low scores refer to good handwriting quality, whereas  
 16 high scores reflect poor handwriting. The task has a very high reported level of interrater  
 17 reliability ( $r = 0.90$ ).

18 **3.3.2.4. Word Reading.** Reading ability was assessed with the Lecture en Une Minute  
 19 single-word reading test administered to the children (LUM, [One minute reading]; Khomsi,  
 20 1999). Children's scores were calculated by counting the number of words correctly read  
 21 within one minute. Their scores were then compared to the test's norms.

#### 22 **3.4. Procedure**

23 The longitudinal study evaluated children's spelling and handwriting performance  
 24 over three years. Data were collected once a year in February–March of 2017 (T1), 2018 (T2)  
 25 and 2019 (T3). At each measurement time, data collection took place over a period of six  
 26 weeks. Each measurement time had two phases, both occurring at children's school in a quiet,  
 27 empty classroom: (i) administration of the control standardised tasks and (ii) administration of  
 28 the experimental task. At each measurement time, the main experimenter collaborated with  
 29 two assistant experimenters for the administration of the control tasks and an engineer for the  
 30 administration of the experimental task. The control tasks were administered to each child  
 31 individually. Vocabulary and nonverbal IQ were only assessed at T1. The durations for the  
 32 control tasks were approximately 45 minutes at T1 and 30 minutes at T2 and T3. The  
 33 experimental task was administered in groups of four children. It lasted approximately 20  
 34 minutes. The instruction was to write down the dictated words at their usual speed. The  
 35 experimenter emphasised that the dictation task would have nothing to do with their school  
 36 results and that even if some words seemed too difficult for them, they should try to write  
 37 them down. It was explained that their writing would be recorded inside the tablets so that we  
 38 would then be able to analyse all their productions. The children were not informed about the

1 focus on handwriting quality and speed. To have enough space to write down the 40 words,  
 2 three A4 sheets for testing were provided for each child. They were attached to the top of the  
 3 tablet with tape. Therefore, the testing conditions were close to how children usually write  
 4 since they had to write on white paper with a Wacom ink pen. Additionally, to guide the  
 5 children throughout the task and to ensure that they would write in the correct space, dashes  
 6 followed by each word's determiner (either – *le* or – *la* [the] or either – *un* or – *une* [a]) were  
 7 placed vertically according to the order used for the dictation. Children had to fill in the blank  
 8 following each determiner. Their production was recorded in real time, with a sample  
 9 frequency of 7/8 ms.

10

## 4. Results

### 4.1. Data analysis

12 The design of the present study involved observations that were nested both within  
 13 children and within words and is referred to as a stimulus sampling design (Wickham et al.,  
 14 2021). While mixed effects models have been widely used to account for such cross-classified  
 15 data structures (Judd et al., 2012; Baayen et al., 2008), these models are limited to univariate  
 16 contexts and are limited for modelling longitudinal designs, accounting for measurement  
 17 errors, and complex structural models (e.g., mediation analyses, Nestler & Back, 2017;  
 18 Wickham et al., 2021). Cross-classified Bayesian structural equation modelling has been  
 19 introduced to address these limitations (Muthén & Asparouhov, 2012) and offer flexible  
 20 capabilities such as the inclusion of multiple observed indicators, longitudinal designs, and  
 21 the inclusion of categorical indicators, as is the case in the present study.

22 In addition to preliminary analyses, our statistical analysis followed a five-step  
 23 strategy in each cohort separately. First, Pearson bivariate correlational analyses of the scores  
 24 for spelling, handwriting speed, and handwriting quality were performed. These correlational  
 25 analyses were computed to quantify the strength of association or to highlight the lack of  
 26 association between the standardised clinical tasks used and the experimental measures  
 27 extracted from the single-word dictation task. Second, variance-component (intercept-only)  
 28 models were estimated to examine the decomposition of the variance in scores between levels  
 29 of analysis. Third, unconditional linear growth models were fitted to investigate the  
 30 significance of time. Fourth, orthographic and graphic complexity were introduced as  
 31 antecedents of our constructs' intercepts and slopes to investigate their relative predictive  
 32 influence on the development of writing skills. As the final step, a unique linear growth model  
 33 was fitted, which allowed us to examine the relations between skills' intercepts and slopes  
 34 and their co-development over time. Preliminary analyses were conducted with IBM SPSS27,  
 35 with the remainder performed using Mplus 8 with full information maximum likelihood  
 36 (FIML) estimation to handle missing data.

37 When analysing cross-classified structural equation models, *Mplus* uses a Bayesian  
 38 approach. The use of Bayesian modelling is motivated by the precision and specificity of  
 39 information about model parameters (e.g., indirect effects in mediation analysis), its  
 40 performance with small samples (i.e., large sample theory is not needed), its efficiency with

1 computationally demanding models (e.g., models with categorical indicators), and the  
2 availability of new modelling techniques (Muthén & Asparouhov, 2012). In contrast to the  
3 statistical frequentist approach, parameters in CC-BSEM are considered random variables and  
4 thus conceptualised with specific distributions. The Bayesian approach also allows  
5 researchers to determine their pre-existing beliefs about the location and dispersion of model  
6 parameters by specifying priors. Importantly, the Bayesian approach is often used for models  
7 that are not computationally possible under the traditional frequentist approach (Muthén &  
8 Asparouhov, 2012), as in the present study, and ‘minimally informative’ prior distributions  
9 are generally preferred to limit the subjectivity in the priors that one may adopt. Previous  
10 research has shown that Bayesian estimation using relevant minimally informative prior  
11 distributions provides results similar to those of traditional modelling, such as maximum  
12 likelihood estimation (Gill, 2014). In other words, when priors are minimally informative and  
13 have a large variance, the likelihood of the data contributes more to the formation of the  
14 posterior distribution than the prior, and the estimate is therefore closer to a maximum  
15 likelihood estimate (Muthén & Asparouhov, 2012).

16 Model parameters in CC-BSEM were estimated using a Monte Carlo Markov chain  
17 algorithm (MCMC) with two chains as the default. Models were first performed using the  
18 minimally informative priors set by default in *Mplus*. For latent variables and observed  
19 indicators at the within level, an inverse Wishart distribution was assumed for the variance  
20 and covariance model parameters at all levels. An inverse gamma distribution was assumed  
21 for the upper-level variances of observed indicators. Threshold, loadings, intercepts, and  
22 means of latent variables were assumed to be normally distributed. When conducting  
23 Bayesian analysis, researchers are strongly invited to examine the sensitivity of their results to  
24 alternative prior distributional specifications and parameter autocorrelations with alternative  
25 thinning parameters (Muthén & Asparouhov, 2012). Given that upper-level variance  
26 components are often very close to zero and that minimally informative prior distributions  
27 might potentially impact the accuracy of these parameters in nested data structures (Browne  
28 & Draper, 2006), Wickham et al. (2021) suggested that upper-level variance components in  
29 nested designs might be better estimated using inverse gamma distributions with very small  
30 specifications. Consequently, we performed additional tests with alternative inverse gamma  
31 distributions (3, 1; 2, 1; 1, 2; .01, .01; .001, .001) for all upper-level variance components.  
32 Consistent with Wickham et al. (2021), assuming an inverse gamma distribution (.001, .001)  
33 resulted in more accurate variance parameter estimates. Additional tests were also performed  
34 to examine the model sensitivity to alternative thinning parameters (i.e., 20, 50, 100). Overall,  
35 these alternative parameterizations yielded similar results and were thus not reported. The  
36 final models reported in this article are modelled with MCMC iterations set at twice the  
37 number at which the proportion scale reduction (PSR) converged, an inverse gamma  
38 distribution (.001, .001) for all upper-level variance components, and thinning set by default  
39 at 1 (Muthén & Asparouhov, 2012). Although researchers are invited to examine their results  
40 using graphically represented posterior distributions (Gill, 2015), we summarised the point  
41 estimates (i.e., median) as well as credible intervals with an associated p-value (i.e., the  
42 credible interval does not include zero) to parallel the traditional frequentist approach and  
43 ease the interpretation process. In contrast to traditional confidence intervals, Bayesian

1 credibility intervals (BCIs) refer to the probability regarding the credible and plausible range  
 2 of estimates for the actual parameter (i.e., 95% probability that the true parameter falls within  
 3 the interval). In addition, we also examined model fit indices when available: (1) the posterior  
 4 predictive P-value (PPP), which indicates a relatively good fit when nonsignificant; (2) the  
 5 deviance (DIC), for which the lowest values indicate better-fitting models; and (3) the  
 6 averaged  $R^2$  across time-specific indicators.

## 7 **4.2. Preliminary Data Analysis**

### 8 **4.2.1. Missing Data**

9 At the within-levels, missing data accounted for 6.60% (T1), 5.33% (T2), and 13.77%  
 10 (T3) across all scores. Across cohorts and at each measurement point, missingness was  
 11 present at both the word (e.g., inattention) and individual levels (e.g., absence due to illness).  
 12 Using full information maximum likelihood (FIML) estimation (Enders, 2010; Newman,  
 13 2014), all models were estimated with scores from all respondents ( $N_{coh1} = 2440$  and  $N_{coh2} =$   
 14  $2240$ ), relying on all participants who completed at least one time point. Under the missing-at-  
 15 random assumption, FIML has been demonstrated to yield unbiased parameter estimates even  
 16 when large amounts of longitudinal missingness are present in the data (e.g., 50%, Enders,  
 17 2010; Newman, 2014).

18 Distributional assumptions related to normality were examined only for speed scores,  
 19 as spelling and handwriting quality scores were categorical indicators. The examination of  
 20 skewness and kurtosis indices for speed yielded satisfactory values when compared to  
 21 commonly reported standards (3.00 and 10.00; Kline, 2015).

### 22 **4.2.2. Correlations Between Spelling, Handwriting Speed and Quality**

23 Pearson bivariate correlational analyses were run between children's scores in spelling,  
 24 handwriting quality and handwriting speed for both the standardised tasks and the  
 25 experimental task at each measurement time (coh1: G2, G3, G4; coh2: G3, G4, G5; see  
 26 Tables 3a and 3b). The standardised measures consisted of spelling accuracy on a sentence  
 27 dictation task (Chronosdictées, Beneath et al., 2006) and handwriting **quality** and speed scores  
 28 on a text-copying task (BHK, Charles et al., 2004). The experimental task was a single-word  
 29 dictation task performed on a digital tablet in which spelling accuracy, handwriting quality  
 30 and speed were assessed. In the case of control measures, the scores used were the scores,  
 31 obtained using test **age or grade norms (i.e., z-scores)**. The measures extracted from the word  
 32 dictation experimental task consisted of children's raw average scores at the task. For  
 33 spelling, success rates for coh 1 were 37.5%, 50.3%, and 59.8%, for grade 2, grade 3, and  
 34 grade 4, respectively. Success rates for coh 2 were 53.2%, 62.9%, and 71.1% for grade 3,  
 35 grade 4, and grade 5, respectively. For coh1, mean handwriting quality scores were 1.70 ( $SD$   
 36  $= 0.97$ ), 1.47 ( $SD = 1.07$ ), and 1.87 ( $SD = 1.09$ ) for Grade 2, Grade 3, and Grade 4,  
 37 respectively. For coh2, mean handwriting quality scores were 1.51 ( $SD = 0.86$ ), 1.22 ( $SD =$   
 38  $1.01$ ), and 1.54 ( $SD = 0.92$ ) for Grade 3, Grade 4, and Grade 5, respectively. Mean speed  
 39 scores for coh1 were 1.34 ( $SD = 0.53$ ), 1.70 ( $SD = 0.62$ ), and 2.07 ( $SD = 0.78$ ) for Grade 2,

1 Grade 3, and Grade 4, respectively. For coh2, mean speed scores were 1.63 ( $SD = 0.65$ ), 1.70  
 2 ( $SD = 0.63$ ), and 1.94 ( $SD = 0.71$ ) for Grade 3, Grade 4, and Grade 5, respectively. More  
 3 details regarding children's performances at the experimental word-dictation task in relation  
 4 to orthographic and graphic levels of complexity can be found in the Appendix section.

5 First, one can notice that for the same ability, namely, spelling, and handwriting  
 6 **quality**, measures from the standardised tasks and the experimental task were strongly  
 7 correlated (e.g., for spelling, all  $r_s > .504$  and all  $p_s < .01$  in Cohort 1, see Table 3a; all  $r_s >$   
 8  $.701$  and all  $p_s < .01$  in Cohort 2, see Table 3b). This demonstrates that even if the tasks were  
 9 different (i.e., sentence dictation for standardised spelling measure vs. single-word dictation  
 10 for experimental spelling measure), they measured **similar** abilities. Concerning handwriting  
 11 speed, measures from the standardised task and from the experimental task (i.e., number of  
 12 words copied in five minutes for handwriting speed standardised measure vs. speed of  
 13 graphomotor execution in cm/s for the experimental measure) were not as strongly correlated.  
 14 However, handwriting speed in the standardised task considers pauses during writing and was  
 15 measured at the text level. In contrast, handwriting speed in the experimental task specifically  
 16 measured graphomotor execution at the word level, without taking pauses into account.  
 17 Finally, in a great majority of cases, the correlations for the same ability were significant over  
 18 time (i.e., between T1 and T2, T2 and T3, and T1 and T3).

19 The analyses highlighted significant correlations between spelling accuracy and  
 20 handwriting speed in both cohorts, indicating that spelling and speed were positively related  
 21 throughout development (e.g., correlations between standardised spelling scores and  
 22 standardised handwriting speed scores in Cohort 1  $r = .297$ ,  $p < .05$  in Grade 2,  $r = .433$ ,  $p <$   
 23  $.01$  in Grade 3 and  $r = .399$ ,  $p < .01$  in Grade 4, see Table 3a; in Cohort 2  $r = .379$ ,  $p < .01$  in  
 24 Grade 3,  $r = .333$ ,  $p < .05$  in Grade 4 and  $r = .618$   $p < .01$  in Grade 5, see Table 3b). Second,  
 25 the correlations demonstrated a negative relation between speed and handwriting quality in  
 26 the experimental word dictation task in both cohorts, revealing that fast handwriting was  
 27 associated with greater numbers of graphic errors (e.g., in Cohort 1 in Grade 4:  $r = .365$ ,  $p <$   
 28  $.05$ , see Table 3a; in Cohort 2 in Grade 5:  $r = .410$ ,  $p < .01$ , see Table 3b).

### 29 **4.3. Cross-classified Growth Curve Models**

#### 30 **4.3.1. Variance Components**

31 Variance component models (intercept-only models) were fitted to investigate  
 32 intraclass correlation coefficients (ICCs) across levels of analysis. For spelling, most  
 33 variability was found at the word level ( $ICC_{\text{word}} = .82$  and  $.77$  for coh1 and coh2) rather than  
 34 at the individual level ( $ICC_{\text{child}} = .09$  and  $.12$  for coh1 and coh2). This pattern of results  
 35 suggests that variability is due to differences between words rather than differences between  
 36 individuals. For speed, a fair amount of variability was found both at the word ( $ICC_{\text{word}} = .40$   
 37 and  $.17$  for coh1 and coh2) and the individual level ( $ICC_{\text{child}} = .50$  and  $.77$  for coh1 and coh2).  
 38 Finally, significant variance components were found at the word ( $ICC_{\text{word}} = .38$  and  $.46$  for  
 39 coh1 and coh2) and the individual level ( $ICC_{\text{child}} = .53$  and  $.38$  for coh1 and coh2) for  
 40 **handwriting quality**. Importantly, all variance components were found significant at the word

1 and individual level. For spelling, the intercept-only model explained similar variance both at  
 2 the word ( $R^2_{\text{word}} = .78$  and  $.89$  for coh1 and coh2) and at the individual level ( $R^2_{\text{child}} = .80$  and  
 3  $.90$  for coh1 and coh2). For speed, the model explained more variance at the word level  
 4 ( $R^2_{\text{word}} = .81$  and  $.84$  for coh1 and coh2) than at the individual level ( $R^2_{\text{child}} = .24$  and  $.61$  for  
 5 coh1 and coh2). Similarly, the model explained more variance at the word level ( $R^2_{\text{word}} = .95$   
 6 and  $.96$  for coh1 and coh2) than at the individual level for handwriting quality ( $R^2_{\text{child}} = .76$   
 7 and  $.62$  for coh1 and coh2).

#### 8 **4.3.2. Unconditional Linear Growth Models**

9 To test the significance of time, unconditional linear growth curve models were fitted  
 10 for each construct and for each cohort separately (see Table 4). For spelling, the results  
 11 showed in both cohorts that a linear trend fit the data well, as indicated by their non-  
 12 significant PPP. In both cohorts, fixed effects were identified at the individual level and  
 13 showed that children tended to improve in spelling over time, though children in coh2  
 14 displayed a weaker trend in improvement ( $B = 0.84$  [0.64; 1.04] and  $0.63$  [0.43; 0.80] for  
 15 coh1 and coh2). Compared to the variance component model, this unconditional linear growth  
 16 model explained an increase of approximately 19.00% and 4.47% of the total variance for  
 17 coh1 at the word and individual levels, respectively. In contrast, the model only explained an  
 18 increase of approximately 7.86% and 2.63% of the total variance in coh2 at the word and  
 19 individual levels, respectively. For speed, the model also fit the data well, as indicated by  
 20 non-significant PPPs and a decreased deviation statistic compared to that for the intercept-  
 21 only model. Children displayed a significant increase in speed over time, with children in  
 22 coh2 having a lower positive trend than children in coh1 ( $B = 0.35$  [0.26; 0.44] and  $0.16$   
 23 [0.10; 0.23] for coh1 and coh2). When examining the change in total variance explained  
 24 compared to that in variance component models, these results showed that the addition of a  
 25 linear trend explained an increase of approximately 0.44% and 23.74% of the total variance  
 26 for coh1 at the word and individual levels, respectively. In coh2, the linear growth model  
 27 explained an increase of approximately 2.90% and 7.93% at the word and individual levels,  
 28 respectively. For **handwriting quality**, the linear growth models fit the data poorly, as  
 29 indicated by significant PPPs in both cohorts, and suggested that no linear change occurred  
 30 over time ( $B = 0.06$  [-0.03; 0.16] and  $0.04$  [-0.04; 0.11] for coh1 and coh2). In coh1, the  
 31 addition of a linear trend explained increases of 1.04% and 4.10% at the word and individual  
 32 levels, respectively. In coh2, these values were 0.30% and 11.60% at the word and individual  
 33 levels, respectively. In all models, all random variance components were significant at both  
 34 the word and individual levels, suggesting that predictors of intercepts and slopes are likely to  
 35 account for some of the variance components in all three constructs.

#### 36 **4.3.3. Conditional Linear Growth Curve Model of Orthographic and Graphic Complexity**

37 From these linear growth curve models, we added the orthographic and graphic  
 38 complexity—as well as their interaction—as predictors of intercept and slope terms for each  
 39 construct separately (see Tables 5 and 6). As these two variables are word-specific predictors,  
 40 random effects were allowed at the within-word levels, and fixed effects were identified only  
 41 at the word level. These analyses yielded contrasting results for each construct. For spelling,

1 orthographic and graphic complexity—as well as their interaction—were significant predictors  
 2 of the intercept in coh1 (i.e., Grade 2). This result suggests that words that are both  
 3 orthographically and graphically complex are spelled the worst. In coh2, only orthographic  
 4 complexity was found to be a predictor of the intercept of spelling (i.e., Grade 3). None of the  
 5 predictors were related to the development of spelling over time. For speed, contrasting  
 6 results were also found when comparing coh1 and coh2. In coh1, whereas neither  
 7 orthographic nor graphic complexity was found to be a predictor of the initial level of speed,  
 8 graphic complexity significantly predicted the development of speed ( $B = -0.10 [-0.17; -$   
 9  $0.03]$ ). In coh2, graphic complexity predicted the initial levels (i.e., grade 3;  $B = -0.19 [-0.33;$   
 10  $-0.04]$ ) but did not predict the development of speed over time. For **handwriting quality**,  
 11 similar results were found among coh1 and coh2. The results showed that only graphic  
 12 complexity was a predictor of the initial levels of handwriting quality in both cohorts (i.e.,  
 13 coh1:  $B = 0.35 [0.18; 0.54]$ ; coh2:  $B = 0.25 [0.03; 0.40]$ ).

#### 14 **4.3.4. Concurrent Development of Spelling, Handwriting Speed, and Handwriting Quality**

15 The last step of the present analyses was to investigate the developmental relations  
 16 between the three constructs over time. For each cohort, we fitted a unique model with the  
 17 three unconditional linear growth models in each cohort separately (see Table 7). Before  
 18 examining the relations between constructs' intercepts and slopes, means and variances of  
 19 intercept and slopes were examined and were found to be strictly similar to the results  
 20 previously identified. In coh1, only the correlation between the intercept of speed and its  
 21 slope was found to be significant. Compared to children with low speed at Grade 2, this  
 22 suggests that children with a higher speed exhibited a lower positive trend over time. In coh2,  
 23 the results showed several significant correlations between the constructs' intercepts and  
 24 slopes. First, the initial levels of speed were related to the initial levels of handwriting quality  
 25 ( $r = .078 [.01; .018]$ ) and initial levels of spelling ( $r = .16 [.01; .36]$ ). However, the initial  
 26 levels of spelling and handwriting quality were not related. Second, the initial levels of  
 27 spelling were significantly related to the development of speed over time ( $r = -.09 [-.20; -$   
 28  $.02]$ ). This finding suggested that children with poorer levels of spelling at Grade 3 tended to  
 29 exhibit a greater increase in speed over time than children with better spelling at Grade 3.  
 30 Overall, these results suggested that the improvements in spelling, speed and handwriting  
 31 quality were rather unrelated, as none of the correlations between the constructs' slopes were  
 32 found to be significant.

### 33 **5. Discussion**

34 The present study addressed the question of the development of writing abilities at the  
 35 word level by assessing for the first time in a longitudinal study the two transcription skills  
 36 with measure of spelling accuracy, handwriting speed and handwriting quality. One hundred  
 37 and seventeen French-speaking children were assessed once a year for three consecutive years  
 38 (coh1: Grades 2–4; coh2: Grades 3–5). They performed a single-word dictation task  
 39 composed of words that varied in orthographic and graphic complexity. Using a cross-  
 40 classified Bayesian structural equation modelling approach, linear growth curve models were

1 conducted in each cohort separately in order to investigate the longitudinal development of  
2 the transcription skills.

### 3 **5.1. Key Findings**

4 This study is the first longitudinal study in which the development of spelling,  
5 handwriting speed and handwriting quality was investigated concurrently. The results  
6 revealed that word spelling and handwriting speed continued to improve until the end of the  
7 study (Grade 5), indicating that these skills have not yet reached a mature level in the later  
8 years of primary school. Conversely, the results revealed no growth in handwriting quality  
9 during the study. This last finding is a valuable contribution to the field of research in writing  
10 development, since the results regarding the age at which children reach a plateau in  
11 handwriting quality were contradictory. Our longitudinal data indicate that the plateau in this  
12 ability had already occurred before the start of the study, i.e., before mid-Grade 2, suggesting  
13 that, in a single word writing context, handwriting quality development is limited to the very  
14 beginning of primary school.

15 Thanks to the cross-classified structural equation modelling analysis, this study  
16 adopted a psycholinguistic approach allowing the investigation of the impact of orthographic  
17 and graphic complexity on spelling and handwriting performances throughout development.  
18 Novel findings were revealed in relation to the graphic complexity of words. Children's  
19 writing performance was impacted by graphic complexity, with handwriting being slower for  
20 graphically difficult words. Graphic complexity even impacted the development of  
21 handwriting speed in the young cohort (coh1: Grades 2–4): children's improvement in speed  
22 was greater for graphically simple words than for graphically complex words. Moreover,  
23 graphic complexity also impacted spelling outcomes, but this effect was limited to the  
24 beginning of the study (Grade 2). To the best of our knowledge, this is the first study with a  
25 large sample of typically developing children showing that the graphomotor cost can impede  
26 spelling in beginning writers. The orthographic complexity of words had a significant  
27 influence on spelling outcomes in both cohorts at the start of the study, with irregular complex  
28 words being produced less accurately. This gap in performance between orthographically  
29 difficult and simple words (i.e., irregular and regular words) was present until the end of the  
30 study (Grade 5). Orthographic complexity did not significantly impact handwriting outcomes,  
31 with orthographically difficult words being produced as legibly and as fast as orthographically  
32 simple words. Finally, this longitudinal study investigated how the three writing abilities  
33 (spelling, handwriting speed and quality) were related to each other. This study demonstrated  
34 a reverse relationship between the two components of handwriting, namely, speed and  
35 quality, indicating that fast handwriting is associated with less legible handwriting. While past  
36 research has concluded that speed and legibility (i.e., measure of handwriting quality using  
37 five aesthetic criteria in the current study) are rather independent from each other, this  
38 experiment suggests a significant association between these two components of handwriting.  
39 Moreover, positive associations between handwriting speed and spelling accuracy were  
40 demonstrated in the present sample, indicating that children who write fast are also those with  
41 strong spelling ability.



## 1 **5.2. Development of the Transcription Skills: Spelling Accuracy, Handwriting Speed** 2 **and Handwriting Quality**

3 The first aim of the study was to examine the development of the three variables  
4 separately. The present study revealed that children's spelling accuracy and handwriting  
5 speed continued to improve during primary school. Throughout the three measurement times,  
6 (coh1: Grade 2 to 4; coh2: Grade 3 to 5), spelling and speed significantly improved, and their  
7 developmental trajectories followed a positive linear trend. These findings are in line with our  
8 predictions and congruent with previous findings (Alves & Limpo, 2015; Graham et al.,  
9 1998). Notably, the slope estimates indicated that the improvement in both spelling and speed  
10 is more important between Grade 2 and Grade 4 (coh1) than between Grade 3 and Grade 5  
11 (coh2). Conversely, the longitudinal data did not reveal improvement in handwriting quality  
12 meaning that it did not change significantly over time in the two cohorts of children (coh1:  
13 Grade 2 to 4; coh2: Grade 3 to 5). Although rarely studied, this result for handwriting quality  
14 is in line with previous findings. An early plateau at the end of Grade 1 was reported in a  
15 longitudinal experiment conducted by Karlsdottir and Stefansson (2002). An explanation for  
16 these findings could be the lack of explicit handwriting instruction after Grade 1 in the  
17 Belgian context of the present study. By beginning the data collection in the second semester  
18 of Grade 2 (coh1) and Grade 3 (coh2), the present study may have not targeted the critical  
19 period for improving **handwriting quality**. In other words, our results suggest that the temporal  
20 window during which handwriting quality develops occurred before the start of our **study**,  
21 between the beginning of Grade 1 and the second semester of Grade 2.

## 22 **5.3. Effect of Word Orthographic and Graphic Complexity on Writing Development**

23 The second aim of the study was to evaluate the influence of the orthographic and  
24 graphic complexity of words, both on the initial levels of transcription abilities at the start of  
25 the study and on the pace of development of these abilities. The experimental dictation task  
26 was composed of words that were either orthographically simple, i.e., regular words, or  
27 orthographically difficult, i.e., irregular words. The same manipulation was used for graphic  
28 complexity, with words being either graphically simple or graphically difficult, i.e.,  
29 containing more abrupt changes in the pen stroke trajectory (Authors, 2018).

30 The orthographic complexity of words revealed a significant influence on spelling  
31 outcomes. The results showed that the orthographic complexity of words was predictive of  
32 children's initial level of spelling accuracy in both cohorts (coh1: Grade 2; coh2: Grade 3).  
33 This result is not surprising, since the dictation task was built to contrast regular words with  
34 inconsistent words, the latter leading to a high percentage of spelling errors. Notably, at the  
35 end of the experiment, children in Grade 5 were spelling accurately less than 50% of the  
36 orthographically complex words, while over 90% of the regular words were spelled correctly.  
37 This finding is in line with past research in which the long lasting impact of word regularity  
38 had been highlighted (Sprengr-Charolles et al., 2003). The results demonstrated that  
39 orthographic complexity did not explain the variability in handwriting skills during the single-  
40 word dictation task, both speed and **quality**, between children at the start of the study, whether  
41 in Grade 2 (coh1) or in Grade 3 (coh3). These findings suggest that handwriting quality and

1 speed are invariant whether words are irregular or regular, which is inconsistent with the  
2 results found for children aged 8–11 by Kandel and Perret (2015) in a single-word copying  
3 task, and with our predictions. A plausible explanation for the absence of influence on speed  
4 could lie in the measure of speed used in the present study, which was an actual measure of  
5 motor execution in terms of the distance covered by seconds (cm/s). This method of  
6 measuring speed did not include pauses and latency. We can hypothesise that, like in past  
7 experiments, orthographically complex words may have led children to think more about  
8 spelling before starting handwriting (Kandel & Perret, 2015) and that pauses may have been  
9 more frequent during handwriting for irregular words than for simple regular words (Sumner  
10 et al, 2013). Measures of latency before writing or pauses during writing would have been  
11 useful to confirm this hypothesis. Moreover, one should recall that the experimental task was  
12 a single-word dictation task with no time constraint. Therefore, children could take as much  
13 time as needed to think before writing and to execute handwriting. It is plausible that in a  
14 different handwriting task with a time constraint, the challenging spelling of irregular words  
15 would have led to poorer handwriting quality, as would be predicted by the capacity theory of  
16 writing (McCutchen, 1996). Our results did not show any significant impact of orthographic  
17 complexity on the way each ability improved. Spelling, handwriting speed and handwriting  
18 quality developed to the same extent whether words were simple (i.e., regular words) or  
19 difficult (i.e., irregular words). This result suggests that the gap in performance between  
20 orthographically simple and complex words observed at T1 for spelling accuracy in both  
21 cohorts remained constant throughout the study, suggesting that the regularity effect is of  
22 similar importance from Grade 2 to Grade 5.

23 The graphic complexity of words revealed numerous significant influences on  
24 children's performance in handwriting speed, spelling and handwriting quality and on their  
25 development. Regarding handwriting speed, the results differed between the two cohorts. At  
26 the beginning of the study, graphic complexity significantly explained handwriting speed in  
27 the older cohort (coh2: Grade 3), whereas it was not a predictor of handwriting speed in the  
28 young cohort (coh1: Grade 2). The expected impact of graphic complexity on handwriting  
29 speed was revealed in the older cohort (Grade 3), who had more automatised handwriting  
30 skills. This finding suggests that when children have a certain level of graphomotor  
31 automatisations, handwriting speed starts to vary according to graphic complexity, with  
32 graphically simple words leading to faster handwriting than graphically difficult words. The  
33 finding that the graphic complexity of words did not impact handwriting speed in Grade 2 can  
34 be explained by children's young age and limited experience in handwriting at the start of the  
35 study. In Grade 2, children may have been invariably slow at handwriting execution, whether  
36 words were graphically simple or complex. Consequently, graphic complexity did not play a  
37 role at this early stage of development. This assumption is in line with previous findings in a  
38 study comparing handwriting speed in children with dyslexia and young typically developing  
39 peers in Grade 2 (Authors, 2020a). Regarding the developmental pace of handwriting speed,  
40 the effect of graphic complexity also differed depending on the cohort. The increase in  
41 handwriting speed was significantly related to graphic complexity in the younger cohort  
42 (coh1: Grades 2–4) but not in the more experienced cohort (coh2: Grades 3–5). In the younger  
43 cohort, handwriting speed developed faster for graphically simple words than for graphically

1 difficult words. As presented above, these young coh1 children did not initially (Grade 2)  
2 present faster handwriting for graphically simple words compared to difficult words.  
3 However, the impact of graphic complexity on handwriting speed seems to have emerged  
4 during the study, since the pace of development varied depending on graphic complexity.  
5 Conversely, the handwriting speed of coh2 children improved equally, regardless of the  
6 graphic complexity of words. This reveals that the gap in speed performance observed in coh2  
7 at the start of the study between graphically simple and graphically difficult words remained  
8 stable over time (coh2: Grades 3–5). In the case of children with more automatised  
9 graphomotor abilities, as we assume was the case for children in Grade 3 at the start of the  
10 study (coh2), the impact of graphic complexity on handwriting speed was already present at  
11 the start of the study and remained stable over time (Grades 3–5). Interestingly, while  
12 handwriting speed has often been interpreted as a reflection of orthographic processes  
13 (Kandel & Perret, 2015; Palmis et al., 2019; Sumner et al., 2013), this study provides a novel  
14 finding regarding the effect of graphic complexity on speed.

15         Regarding spelling accuracy, graphic complexity explained a significant portion of the  
16 performance variability among children at the start of the study in the young cohort (Grade 2).  
17 Moreover, the interaction between orthographic and graphic complexity was significant, with  
18 difficult words leading to less accurate spelling in beginning writers in Grade 2. Conversely,  
19 this effect of graphic complexity was not present in the older cohort, who started in Grade 3.  
20 In other words, children in Grade 2 spelled graphically complex words less accurately than  
21 graphically simple words, while children in Grade 3 were not impacted by the manipulation  
22 of graphic complexity. This different finding can potentially be explained by the capacity  
23 theory of writing (McCutchen, 1996). Indeed, young children (coh1) had to recruit more  
24 cognitive resources for graphomotor processes than coh2 children, since their handwriting  
25 abilities were not as mature and automatised. It can then be assumed that in coh1 (Grade 2),  
26 the increasing graphic complexity of words required children to allocate more resources to the  
27 handwriting processes at the expense of spelling. Moreover, the results showed that the  
28 development of spelling over time did not depend on graphic complexity. Children from the  
29 two cohorts improved spelling accuracy over time to the same extent whether words were  
30 graphically simple or complex.

31         Regarding handwriting **quality** the findings highlighted in both cohorts a significant  
32 impact of graphic complexity on children's initial performance (coh1: Grade 2; coh2: Grade  
33 3). Not surprisingly, graphically difficult words led to poorer handwriting quality than  
34 graphically simple words (Authors, 2018). The results showed that graphic complexity had no  
35 significant impact on the development of handwriting quality. This means that handwriting  
36 quality developed at the same pace for graphically simple and difficult words. These results  
37 indicated that the impact of graphic complexity on handwriting quality remained stable until  
38 the end of the study (coh1: Grade 4; coh2: Grade 5), with graphically difficult words still  
39 being produced less legibly than graphically simple words for the oldest children. These  
40 findings are novel, since handwriting quality has only rarely been investigated (Barnett et al.,  
41 2018; Caravolas et al., 2020; Authors, 2018) and, to the best of our knowledge, never been  
42 studied in relation to graphic complexity.

#### 1 **5.4. Relations Between Spelling, Handwriting Speed and Handwriting Quality**

2 The last objective of the present study was to examine the developmental relations  
3 between spelling, handwriting speed, and handwriting quality to shed light on the potential  
4 reciprocal influences between transcription skills. In addition, the correlational analyses  
5 allowed us to further refine our understanding of the relationships between transcription  
6 skills. First, while spelling and handwriting speed showed continuous development until the  
7 end of the study, our analyses did not reveal a significant impact of the improvement in one  
8 skill on the improvement in the other. This is visible in the absence of significant correlations  
9 between the slopes for each skill. In other words, the development of spelling was not  
10 explained by the development of speed, and handwriting speed improvement was not  
11 explained by the improvement in spelling accuracy.

12 The results revealed a significant association between spelling accuracy and  
13 handwriting speed in coh2 (Grade 3 to 5), with spelling in Grade 3 influencing both the initial  
14 level and the development of speed. The analyses showed that the pace of development of  
15 speed was significantly related to spelling performance at the start of the study (Grade 3).  
16 This means that poor spellers in Grade 3 improved their speed of handwriting to a greater  
17 extent than children with higher spelling accuracy. To interpret this finding, it is interesting to  
18 add that correlational analyses revealed a positive association between spelling accuracy and  
19 handwriting speed in both cohorts throughout development (coh1: Grades 2–4; coh2: Grades  
20 3–5). It can then be assumed that the poor spellers in Grade 3 were also slower at  
21 handwriting. Therefore, the poor spellers, also slow at handwriting, possibly had more room  
22 for improving their handwriting speed than the better spellers.

23 A last significant finding from the analyses concerns the relationship between  
24 handwriting speed and handwriting quality in Grade 3 (coh2). The analyses revealed that the  
25 initial levels of handwriting speed and handwriting quality were negatively related. This  
26 means that the fast children were the ones with poorer handwriting quality in Grade 3, as  
27 measured by the presence of aesthetic errors. However, it is important to remind that a word  
28 containing aesthetic errors in the present study did not indicate legibility issues, as  
29 handwriting can still be easily decoded even when the word is not composed of letters  
30 perfectly formed or aligned with one another. This negative relationship between handwriting  
31 speed and handwriting quality was also observed in both cohorts, with significant correlations  
32 at different grades in the single-word dictation task (coh1: Grades 2 and 4; coh2: Grades 3 and  
33 5). **This relationship is in line with a commentary published by Graham (2018), raising the  
34 dilemma that students face between writing fast or writing neatly. While this observation was  
35 made at the text level for young adults, the present study addressed for the first time the issue  
36 of the relationship between speed and handwriting quality in children at the word level.**

37 In the younger cohort (Grades 2–4), the results revealed that children's handwriting  
38 speed at the beginning of the study was negatively related to the development of the same  
39 ability. In other words, the improvement in speed execution between Grade 2 and Grade 4  
40 was greater for children who started with slow handwriting. This is not surprising, since slow

1 children had greater room for progress than children who had more advanced and automated  
2 handwriting abilities at the beginning of the study.

3 Our analyses did not bring any significant result regarding the developing relationship  
4 between spelling and handwriting quality. However, a significant cross-sectional positive  
5 correlation between spelling accuracy and handwriting quality, limited to the beginning of the  
6 study, was found in the younger cohort only. Significant correlations were present between  
7 spelling at the standardised task (i.e., sentence dictation) and quality in the standardised task  
8 (i.e., text copying) but not in the single-word dictation context. This relation disappeared after  
9 Grade 3, suggesting that spelling accuracy and handwriting quality are no longer related once  
10 children have more automatised handwriting, which can be understood in the framework of  
11 McCutchen's capacity of writing theory (1996). This interpretation is congruent with the  
12 above-mentioned findings demonstrating that graphic complexity negatively impacted  
13 spelling accuracy only in Grade 2 (coh1) and not in Grade 3 (coh2).

#### 14 **5.5. Study Limitations and Perspectives**

15 This section addresses the present study's limitations, which can be useful for  
16 researchers designing experiments in the field of writing development. The first limitation  
17 concerns the experimental task used in the present experiment, which was a single-word  
18 dictation task. Word dictations are exclusively related to the context of spelling evaluation at  
19 school, which limits the ecological validity of such writing tasks. Adding data from a sentence  
20 dictation task could be a way of assessing children's writing abilities in a more ecological  
21 way, since writing in most school activities (e.g., text generation, taking notes during lessons)  
22 and personal contexts (e.g., writing letters) is not limited to single-word writing. Therefore,  
23 we strongly encourage researchers to collect longitudinal data on spelling, handwriting speed  
24 and handwriting quality in various writing contexts.

25 A second limitation of the present study concerns the measurement of speed, which  
26 reflects the speed of graphomotor execution. Future experiments should consider several  
27 dynamics of handwriting to investigate not only the graphomotor speed of execution but also  
28 the total writing durations and pause durations. Having measures that better represent the time  
29 course of writing will help in understanding how spelling and handwriting are related, since  
30 latency times and pauses within writing are typical manifestations of orthographic processes  
31 (Sumner et al., 2013).

32 A third limitation is the relatively small window of time covered by the study. Each  
33 cohort was followed for a period of three years, from Grade 2 to Grade 4 in coh1 and from  
34 grade 3 to Grade 5 in coh2. Past literature has concluded that handwriting legibility  
35 development may be limited to the very beginning of explicit teaching. It would have been  
36 relevant to start the study in Grade 1 to capture the critical improvement phase of handwriting  
37 quality. Along the same lines, since speed of handwriting and spelling accuracy continue  
38 developing even in the later grades, it would have been interesting to keep following the same  
39 participants at least until these skills reach a plateau. The current study did not enable us to  
40 understand when each transcription skill reaches a mature level. However, designing

1 longitudinal experiments covering such a large window of time can seem unrealistic because  
2 longitudinal designs are known to be challenging to conduct. Nevertheless, even if they  
3 cannot cover the whole period of childhood development, more longitudinal studies are  
4 needed to better understand writing development.

5 A fourth limitation concerns the limited assessment of teaching and motivational  
6 factors. Indeed, even if children all came from two primary-schools in which teachers were  
7 using the same educational method for spelling and handwriting instruction, it would have  
8 been interesting to gather more information about teaching practices. In the same vein, it  
9 would have been useful to collect data regarding participants' motivation towards writing.  
10 These factors, i.e., teaching effect and motivational variables (Camacho et al., 2021), could  
11 also explain part of writing development, as well as the significant differences highlighted  
12 between cohorts.

13 Finally, readers should keep in mind that the present longitudinal study involved data  
14 collected in a cursive handwriting context in a French-speaking sample, and French  
15 orthography is opaque. Handwriting cursive and script styles are known to differ in terms of  
16 graphomotor gestures, i.e., continuity within the word vs. pauses between each letter.  
17 Moreover, differences in the pace of spelling have already been documented in accordance  
18 with language consistency. Therefore, the relationship between spelling and handwriting  
19 could possibly develop differently in script and cursive contexts and in opaque compared to  
20 transparent orthographies. By replicating the study in other educational and linguistic  
21 contexts, future research could highlight how the development of spelling and handwriting is  
22 dependent on language consistency as well as handwriting style.

## 23 **5.6. Educational Implications**

24 The present study highlights the long-lasting challenge represented by writing  
25 development. The two transcription skills, word spelling and handwriting, were still growing  
26 until the end of the study, i.e., Grades 4 and 5. While handwriting is taught only in the very  
27 beginning of primary school (Graham et al., 2008), the results support keeping handwriting  
28 practice at the centre of focus longer. Past experiments have already highlighted the need to  
29 focus more attention on the development of graphomotor skills during primary school  
30 (Graham, 2010; Feder & Majnemer, 2007), but teachers frequently report that they lack tools  
31 and methods to teach handwriting skills (Graham et al., 2008). By highlighting the influence  
32 of graphic complexity on writing outcomes, the present findings encourage future  
33 experiments to assess the efficacy of teaching handwriting with a particular focus on  
34 graphically complex segments. An important finding arising from the present study concerns  
35 the reverse relationship between handwriting speed and quality. This finding suggests that, at  
36 the single word level, having fast handwriting is associated with poorer handwriting quality.  
37 In contrast, children with high handwriting quality write slowly. To understand this finding,  
38 one can consider his/her own adult handwriting: to be efficient when taking notes, speed is  
39 inevitably favoured over handwriting quality.

1 Overall, this longitudinal study highlighted different facets of the long-lasting  
 2 challenge implied by learning to write words. While spelling and handwriting speed are  
 3 positively related, handwriting speed and handwriting quality are negatively related during  
 4 development. Through the study of orthographic and graphic complexity, the results showed  
 5 that spelling, handwriting speed and handwriting quality influence each other during writing.  
 6 Notably, graphic complexity had a significant impact on the development of handwriting  
 7 speed and on spelling accuracy in beginning writers (Grade 2). Improvement in one ability  
 8 may positively influence the other by reducing cognitive constraints. Therefore, handwriting  
 9 automatisations, by reducing the cognitive load for children, appears crucial for writing  
 10 development. However, even with more advanced handwriting skills, it is important to keep  
 11 in mind that each writing production is the result of a multitude of cognitive processes active  
 12 in parallel and influencing each other. Both transcription skills, i.e., spelling and handwriting,  
 13 need time and practice opportunities to develop. Even if spelling and handwriting progress  
 14 greatly during primary school, this study suggests that mature levels are not yet reached at the  
 15 end of primary school.

16

### References

- 17 Abbott, R. D., Berninger, V. W., & Fayol, M. (2010). Longitudinal relationships of levels of  
 18 language in writing and between writing and reading in grades 1 to 7. *Journal of*  
 19 *Educational Psychology*, 102, 281-298. doi:10.1037/a0019318
- 20 Alves, R. A., & Limpo, T. (2015). Progress in written language bursts, pauses, transcription,  
 21 and written composition across schooling. *Scientific Studies of Reading*, 19(5), 374-391.  
 22 doi:10.1080/10888438.2015.1059838
- 23 Arfé, B., Corato, F., Pizzocaro, E., & Merella, A. (2020). The effects of script and orthographic  
 24 complexity on the handwriting and spelling performance of children with dyslexia. *Journal*  
 25 *of Learning Disabilities*, 53(2), 96-108. doi:10.1177/0022219419892845
- 26 Bahr, R. H., Silliman, E. R., Berninger, V. W., & Dow, M. (2012). Linguistic pattern analysis  
 27 of misspellings of typically developing writers in grades 1–9. *Journal of Speech,*  
 28 *Language, and Hearing Research*. 1587–1599. doi:10.1044/1092-4388(2012/10-0335)
- 29 Bara, F., & Morin, M. F. (2013). Does the handwriting style learned in first grade determine  
 30 the style used in the fourth and fifth grades and influence handwriting speed and  
 31 quality? A comparison between french and quebec children. *Psychology in the Schools*,  
 32 50(6), 601-617. doi:10.1002/pits.21691
- 33 Barnett, A. L., Connelly, V., & Miller, B. (2019). The interaction of reading, spelling, and  
 34 handwriting difficulties with writing development. *Journal of Learning*  
 35 *Disabilities*, 53(2), 92-95. doi:10.1177/0022219419894565
- 36 Barnett, A. L., Prunty, M., & Rosenblum, S. (2018). Development of the handwriting  
 37 legibility scale (HLS): a preliminary examination of reliability and validity. *Research in*  
 38 *Developmental Disabilities*, 72, 240-247. doi:10.1016/j.ridd.2017.11.013
- 39 Beneath, B., Boutard, C., & Alberti, C. (2006). Chronosdictées: outils d'évaluation des  
 40 performances orthographiques avec et sans contraintes temporelles: du CE1 à la  
 41 troisième. Paris: Ortho Edition.

- 1 Bosga-Stork, I. M., Bosga, J., Ellis, J. L., & Meulenbroek, R. G. (2016). Developing  
2 interactions between language and motor skills in the first three years of formal  
3 handwriting education. *British Journal of Education, Society and Behavioural Science*,  
4 12(1), 1–13. doi:10.9734/bjesbs/2016/20703
- 5 Breadmore, H. L., & Deacon, S. H. (2019). Morphological processing before and during  
6 children's spelling. *Scientific Studies of Reading*, 23(2), 178-191.  
7 doi:10.1080/10888438.2018.1499745
- 8 Browne, W. J., & Draper, D. (2006). A comparison of Bayesian and likelihood-based  
9 methods for fitting multilevel models. *Bayesian Analysis*, 1(3), 473-514.  
10 doi:10.1214/06-ba117
- 11 Caravolas, M., Downing, C., Hadden, C. L., & Wynne, C. (2020). Handwriting legibility and  
12 its relationship to spelling ability and age: evidence from Monolingual and Bilingual  
13 children. *Frontiers in Psychology*, 11. doi:10.3389/fpsyg.2020.01097
- 14 Casalis, S., Deacon, S. H., & Pacton, S. (2011). How specific is the connection between  
15 morphological awareness and spelling? A study of French children. *Applied*  
16 *Psycholinguistics*, 32(3), 499. doi:10.1017/s014271641100018x
- 17 Charles, M., Soppelsa, R., & Albaret, J.-M. (2004). BHK: échelle d'évaluation rapide de  
18 l'écriture chez l'enfant. *EAP, Éditions et Applications Psychologiques* (2004).
- 19 Chartrel, E., & Vinter, A. (2004). L'écriture: Une activité longue et complexe à acquérir  
20 [Writing acquisition: A long, complex process]. *A.N.A.E. Approche*  
21 *Neuropsychologique des Apprentissages chez l'Enfant*, 16(3[78]), 174-180.
- 22 Chliounaki, K., & Bryant, P. (2007). How children learn about morphological spelling  
23 rules. *Child Development*, 78(4), 1360-1373. doi:10.1111/j.1467-8624.2007.01070.x
- 24 Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route  
25 cascaded model of visual word recognition and reading aloud. *Psychological*  
26 *Review*, 108(1), 204–256. doi:10.1037/0033-295x.108.1.204
- 27 Deacon, S. H., & Bryant, P. (2006). This turnip's not for turning: Children's morphological  
28 awareness and their use of root morphemes in spelling. *British journal of developmental*  
29 *psychology*, 24(3), 567-575.
- 30 Delattre, M., Bonin, P., & Barry, C. (2006). Written spelling to dictation: Sound-to-spelling  
31 regularity affects both writing latencies and durations. *Journal of Experimental*  
32 *Psychology: Learning, Memory, and Cognition*, 32(6), 1330-1340. doi:10.1037/0278-  
33 7393.32.6.1330
- 34 Downing, C., & Caravolas, M. (2020). Prevalence and Cognitive Profiles of Children With  
35 Comorbid Literacy and Motor Disorders. *Frontiers in psychology*, 11, 3347.  
36 doi:10.3389/fpsyg.2020.573580
- 37 Dunn, L. M., Dunn, L. M., & Theriault-Whalen, C. (1993). *EVIP: échelle de vocabulaire en*  
38 *images Peabody*. Pearson Canada Assessment.
- 39 Enders, C. K. (2010). *Applied missing data analysis*. Guilford press.
- 40 Feder, K. P., & Majnemer, A. (2007). Handwriting development, competency, and  
41 intervention. *Developmental Medicine & Child Neurology*, 49(4), 312-317.  
42 doi:10.1111/j.1469-8749.2007.00312.x



- 1 Gill, J. (2014). *Bayesian methods: A social and behavioral sciences approach* (20). CRC  
2 press.
- 3 Graham, S. (2010). Want to Improve Children's Writing? *The Education Digest*, 76(1), 49.
- 4 Graham, S. (2018). Handwriting instruction: a commentary on five studies. *Reading and*  
5 *Writing: An Interdisciplinary Journal*, 31(6), 1367-1377. doi:10.1007/s11145-018-  
6 9854-5
- 7 Graham, S., Berninger, V., Weintraub, N., & Schafer, W. (1998). Development of  
8 handwriting speed and legibility in grades 1–9. *The Journal of Educational Research*,  
9 92, 42-52. doi:10.1080/00220679809597574
- 10 Graham, S., Harris, K. R., Mason, L., Fink-Chorzempa, B., Moran, S., & Saddler, B. (2008).  
11 How do primary grade teachers teach handwriting? A national survey. *Reading and*  
12 *Writing: An Interdisciplinary Journal*, 21(1-2), 49-69. doi:10.1007/s11145-007-9064-z
- 13 Graham, S., Struck, M., Santoro, J., & Berninger, V. W. (2006). Dimensions of Good and  
14 Poor Handwriting Legibility in First and Second Graders: Motor Programs, Visual-  
15 Spatial Arrangement, and Letter Formation Parameter Setting. *Developmental*  
16 *Neuropsychology*, 29(1), 43-60. .doi:10.1207/s15326942dn2901\_4
- 17 Hamstra-Bletz, E., De Bie, J., & Brinker, B. P. L. M. (1987). *Beknopte beoordelingsmethode*  
18 *voor kinderhandschriften: experimentele versie*. Swets & Zeitlinger.
- 19 Jones, D., & Christensen, C. A. (1999). Relationship between automaticity in handwriting and  
20 students' ability to generate written text. *Journal of Educational Psychology*, 91(1), 44-  
21 49. doi:10.1037/0022-0663.91.1.44
- 22 Kandel, S., & Perret, C. (2015). How does the interaction between spelling and motor  
23 processes build up during writing acquisition? *Cognition*, 136, 325-336.  
24 doi:10.1016/j.cognition.2014.11.014
- 25 Karlsdottir, R., & Stefansson, T. (2002). Problems in developing functional  
26 handwriting. *Perceptual and Motor Skills*, 94(2), 623–662.  
27 doi:10.2466/pms.2002.94.2.623
- 28 Khomsi, A. (1999). Lecture en une minute (LUM). *LMC-R: Epreuve d'évaluation de la*.
- 29 Martinet, C., Valdois, S., & Fayol, M. (2004). Lexical orthographic knowledge develops from  
30 the beginning of literacy acquisition. *Cognition*, 91(2), B11-B22.  
31 doi:10.1016/j.cognition.2003.09.002
- 32 McCutchen, D. (1996). A capacity theory of writing: Working memory in  
33 composition. *Educational Psychology Review*, 8, 299-325. doi:10.1007/BF01464076
- 34 Medwell, J., & Wray, D. (2007). Handwriting: what do we know and what do we need to  
35 know? *Literacy*, 41, 10-15. doi:10.1111/j.1467-9345.2007.00453.x
- 36 Morin, M.-F., Lavoie, N., & Montésinos-Gelet, I. (2012). The effects of manuscript, cursive  
37 or manuscript/cursive styles on writing development in Grade 2. *Language and*  
38 *Literacy*, 14(1), 110. doi:10.20360/g21s3v
- 39 Muthén, B., & Asparouhov, T. (2012). Bayesian structural equation modeling: a more flexible  
40 representation of substantive theory. *Psychological Methods*, 17(3), 313–335.  
41 doi:10.1037/a0026802
- 42 Nestler, S., & Back, M. D. (2017). Using cross-classified structural equation models to  
43 examine the accuracy of personality judgments. *Psychometrika*, 82(2), 475–497.  
44 doi:10.1007/s11336-015-9485-6

- 1 New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical  
2 database. *Behavior Research Methods, Instruments, & Computers*, 36(3), 516-524.  
3 doi:10.3758/bf03195598
- 4 Newman, D. A. (2014). Missing data: Five practical guidelines. *Organizational Research*  
5 *Methods*, 17(4), 372-411. doi:10.1177/1094428114548590
- 6 Overvelde, A., & Hulstijn, W. (2011). Handwriting development in grade 2 and grade 3  
7 primary school children with normal, at risk, or dysgraphic characteristics. *Research in*  
8 *Developmental Disabilities*, 32, 540-548. doi:10.1016/j.ridd.2010.12.027
- 9 Pacton, S., Perruchet, P., Fayol, M., & Cleeremans, A. (2001). Implicit learning out of the lab:  
10 The case of orthographic regularities. *Journal of Experimental Psychology:*  
11 *General*, 130(3), 401. doi: 10.1037/0096-3445.130.3.401
- 12 Palmis, S., Velay, J.-L., Fabiani, E., Nazarian, B., Anton, J.-L., Habib, M., Kandel, S., &  
13 Longcamp, M. (2019). The impact of spelling regularity on handwriting production: A  
14 coupled fMRI and kinematics study. *Cortex: A Journal Devoted to the Study of the*  
15 *Nervous System and Behavior*, 113, 111-127. doi:10.1016/j.cortex.2018.11.024
- 16 Pontart, V., Bidet-Ildei, C., Lambert, E., Morisset, P., Flouret, L., & Alamargot, D. (2013).  
17 Influence of handwriting skills during spelling in primary and lower secondary  
18 grades. *Frontiers in Psychology*, 4, 818, 1-9. doi:10.3389/fpsyg.2013.00818
- 19 Pothier, B., & Pothier, P. (2003). *Échelle d'acquisition en orthographe lexicale*  
20 *(EOLE)*. [Acquisition scale for lexical spelling]. Paris, France: Retz.
- 21 Prunty, M., & Barnett, A. L. (2017). Understanding handwriting difficulties: A comparison of  
22 children with and without motor impairment. *Cognitive Neuropsychology*, 34(3-4), 205-  
23 218. doi:10.1080/02643294.2017.1376630
- 24 Sprenger-Charolles, L., Siegel, L. S., Béchenec, D., & Serniclaes, W. (2003). Development  
25 of phonological and orthographic processing in reading aloud, in silent reading, and in  
26 spelling: A four-year longitudinal study. *Journal of Experimental Child*  
27 *Psychology*, 84(3), 194-217. doi:10.1016/s0022-0965(03)00024-9
- 28 Sprenger-Charolles, L., Siegel, L. S., & Bonnet, P. (1998). Reading and spelling acquisition  
29 in French: The role of phonological mediation and orthographic factors. *Journal of*  
30 *Experimental Child Psychology*, 68(2), 134-165. doi:10.1006/jecp.1997.2422
- 31 Sumner, E., Connelly, V., & Barnett, A. L. (2013). Children with dyslexia are slow writers  
32 because they pause more often and not because they are slow at handwriting  
33 execution. *Reading and Writing: An Interdisciplinary Journal*, 26(6), 991-1008.  
34 doi:10.1007/s11145-012-9403-6
- 35 Tainturier, M.-J., & Rapp, B. (2001). *The spelling process*. In B. Rapp (Ed.), *The Handbook*  
36 *of Cognitive Neuropsychology: What Deficits Reveal about the Human Mind* (p. 263-  
37 289). Psychology Press.
- 38 Treiman, R. (2017). Learning to spell: Phonology and beyond. *Cognitive*  
39 *Neuropsychology*, 34(3-4), 83-93. doi:10.1080/02643294.2017.1337630
- 40 Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement*  
41 *Science*, 10(2), 165-191. doi:10.1016/0167-9457(91)90003-G
- 42 Wechsler, D. (2005). *Échelle d'intelligence de Wechsler pour enfants (4ème éd.)* [Wechsler  
43 Intelligence Scale for Children]. Paris, France: Éditions du Centre de Psychologie  
44 Appliquée.

- 1 Wickham, R. E., Hardy, K. K., Buckman, H. L., & Lepovic, E. (2021). Comparing cross-  
2 classified mixed effects and Bayesian structural equations modeling for stimulus  
3 sampling designs: A simulation study. *Journal of Experimental Social Psychology*, 92,  
4 104062.
- 5 Authors (2009)  
6 Authors (2018)  
7 Authors (2020a)  
8 Authors (2020b)  
9

In review

Table 1  
*Children's Scores on Control Measures at Each Measurement Time.*

Control Measure	Cohort 1								
	T1, Grade 2, <i>N</i> = 59, 28 girls			T2, Grade 3, <i>N</i> = 60, 28 girls			T3, Grade 4, <i>N</i> = 57, 27 girls		
	<i>M</i>	<i>SD</i>	Range	<i>M</i>	<i>SD</i>	Range	<i>M</i>	<i>SD</i>	Range
Age (years;months)	7;6	0.4	7;1 - 8;7	8;6	0.4	8;1 - 9;7	9;5	0.4	9;1 - 10;7
Non-verbal IQ	-0.32	0.95	-2.00 - 1.33	—	—	—	—	—	—
Vocabulary	0.38	1.32	-2.00 - 3.40	—	—	—	—	—	—
Spelling Accuracy	-0.66	1.15	-3.84 - 1.14	-0.32	0.80	-1.84 - 1.43	-0.86	1.12	-4.32 - 1.65
Word Reading	0.48	0.68	-0.80 - 2.29	0.57	0.78	-1.02 - 2.34	0.55	0.89	-1.51 - 2.08
Handwriting Quality	-0.54	1.00	-2.75 - 1.43	-1.09	1.24	-3.8 - 1.89	-1.13	1.61	-3.86 - 2.14
Handwriting Speed	0.19	0.85	-1.47 - 2.20	0.41	1.00	-1.32 - 2.59	0.26	0.88	-1.08 - 2.05
Control Measure	Cohort 2								
	T1, Grade 3, <i>N</i> = 55, 28 girls			T2, Grade 4, <i>N</i> = 56, 28 girls			T3, Grade 5, <i>N</i> = 53, 26 girls		
	<i>M</i>	<i>SD</i>	Range	<i>M</i>	<i>SD</i>	Range	<i>M</i>	<i>SD</i>	Range
Age (years;months)	8;7	0.4	8;0 - 9;8	9;7	0.4	9;0 - 10;7	10;6	0.4	10;0 - 11;7
Non-verbal IQ	0.12	0.93	-2.00 - 2.33	—	—	—	—	—	—
Vocabulary	0.87	0.94	-1.78 - 3.20	—	—	—	—	—	—
Spelling Accuracy	-0.15	0.87	-2.56 - 1.55	-0.49	1.06	-4.23 - 1.34	-0.79	1.16	-3.47 - 1.34
Word Reading	0.61	0.88	-0.83 - 2.89	0.65	0.88	-0.84 - 2.51	0.97	2.82	-1.37 - 1.98
Handwriting Quality	-0.91	1.62	-5.16 - 1.89	-0.66	1.58	-4.43 - 3.57	-0.76	1.72	-6.83 - 2.03
Handwriting Speed	0.74	1.03	-1.70 - 4.67	0.46	0.93	-1.47 - 3.05	0.84	0.86	-0.98 - 3.22

*Note.* The scores presented in this table are **z-scores** calculated by comparing children's raw scores to the clinical tests' norms for their age or grade (see Measures section for more details). These scores have a mean of 0 and a standard deviation of 1. They allow positioning children's performances in comparison to the average performances for their age or grade. **Z-scores** below -2 SD indicate pathological performances, and scores below -1.5 SD indicate low performances. Conversely, scores above +2 SD indicate exceptionally high performances.

Table 2

*Means and Standard Deviations on Words' Characteristics per List and Equivalence Between Lists*

Words characteristics	O-simple ; G-simple		O-difficult ; G-simple		O-simple ; G-difficult		O-difficult ; G-difficult	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Number of letters	5.24 <sup>a</sup>	0.91	5.38 <sup>ab</sup>	0.53	6.11 <sup>ab</sup>	0.85	6.27 <sup>b</sup>	0.67
Digram frequency	2.52	0.35	2.85	0.38	2.81	0.29	2.60	0.32
Success rate for G2 (EOLE)	90.90 <sup>a</sup>	8.14	12.33 <sup>b</sup>	6.16	85.84 <sup>a</sup>	7.91	12.91 <sup>b</sup>	10.08
Graphic complexity index	13.24 <sup>a</sup>	2.21	13.31 <sup>a</sup>	1.56	22.63 <sup>b</sup>	2.42	23.20 <sup>b</sup>	2.81
Items	<i>cabine</i>	<i>cabin</i>	<i>caddie</i>	<i>trolley</i>	<i>borne</i>	<i>terminal</i>	<i>accord</i>	<i>deal</i>
	<i>carte</i>	<i>card</i>	<i>cadet</i>	<i>cadet</i>	<i>branche</i>	<i>branch</i>	<i>annexe</i>	<i>appendix</i>
	<i>cheval</i>	<i>horse</i>	<i>coulis</i>	<i>grout</i>	<i>bravo</i>	<i>cheers</i>	<i>boxeur</i>	
	<i>dictée</i>	<i>dictation</i>	<i>craie</i>	<i>chalk</i>	<i>brique</i>	<i>brick</i>	<i>brebis</i>	<i>boxer</i>
	<i>gauche</i>	<i>left</i>	<i>deuil</i>	<i>grief</i>	<i>chambre</i>	<i>room</i>	<i>horaire</i>	<i>ewe</i>
	<i>lire</i>	<i>read</i>	<i>gueule</i>	<i>mouth</i>	<i>nombre</i>	<i>number</i>	<i>horreur</i>	<i>schedule</i>
	<i>lundi</i>	<i>Monday</i>	<i>laitue</i>	<i>lettuce</i>	<i>ouvrage</i>	<i>book</i>	<i>kiosque</i>	
	<i>papa</i>	<i>dad</i>	<i>mulot</i>	<i>mouse</i>	<i>poivre</i>	<i>pepper</i>	<i>membre</i>	<i>horror</i>
	<i>police</i>	<i>police</i>	<i>talent</i>	<i>talent</i>	<i>sabre</i>	<i>sword</i>	<i>sirop</i>	<i>booth</i>
	<i>robe</i>	<i>dress</i>	<i>trait</i>	<i>trait</i>	<i>score</i>	<i>score</i>	<i>ressort</i>	<i>member</i>
								<i>syrup</i>
								<i>spring</i>

*Note.* O-simple = orthographically simple words; O-difficult = orthographically difficult words; G-simple = graphically simple words; G-difficult = graphically difficult words; G2 = Grade 2; EOLE = Echelle d'acquisition en orthographe lexicale [lexical spelling acquisition scale]; Pothier & Pothier, 2003). Values with different superscript letters a and b differ significantly (Bonferroni contrasts all  $ps < .001$ ).

Table 3a

*Correlations Between Experimental and Control Measures of Spelling and Handwriting Abilities at the three Measurement Times in Cohort 1*

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Experimental single-word dictation task																	
1. Spelling Accuracy G2	-																
2. Spelling Accuracy G3	.650**	-															
3. Spelling Accuracy G4	.566**	.748**	-														
4. Handwriting Speed G2	-.079	-.1	-.031	-													
5. Handwriting Speed G3	-.036	.055	.021	.576**	-												
6. Handwriting Speed G4	-.079	.027	.062	.27	.508**	-											
7. Handwriting Quality G2 <sup>a</sup>	.085	-.174	.012	.285*	.183	.014	-										
8. Handwriting Quality G3 <sup>a</sup>	-.141	-.140	.026	.215	.204	.178	.693**	-									
9. Handwriting Quality G4 <sup>a</sup>	-.205	-.400**	-.226	.156	.076	.356*	.542**	.652**	-								
Standardised spelling task (Chronosdictée) <sup>b</sup>																	
10. Spelling Accuracy G2	.615**	.650**	.511**	-.056	-.056	.048	-.291*	-.491**	-.356*	-							
11. Spelling Accuracy G3	.600**	.727**	.711**	.136	.111	.248	-.077	-.120	-.221	.546**	-						
12. Spelling Accuracy G4	.504**	.705**	.772**	.166	.165	.191	.055	.083	-.186	.458**	.762**	-					
Standardised handwriting copying task (BHK) <sup>b</sup>																	
13. Handwriting Speed G2	.299*	.299*	.483**	.293*	.289*	.099	-.072	-.070	.036	.297*	.309*	.236	-				
14. Handwriting Speed G3	.180	.244	.369**	.341*	.341*	.212	-.012	-.006	-.001	.051	.433**	.221	.695**	-			
15. Handwriting Speed G4	.145	.235	.491**	.349*	.258	.316*	.173	.181	.069	.041	.404**	.399**	.611**	.717**	-		
16. Handwriting Quality G2 <sup>a</sup>	-.065	-.221	-.214	.066	-.192	-.252	.403**	.358**	.474**	-.339*	-.145	-.194	-.057	-.111	-.185	-	
17. Handwriting Quality G3 <sup>a</sup>	-.023	-.276*	-.222	.044	.063	-.085	.492**	.636**	.579**	-.365**	-.377**	-.260	.079	-.059	-.053	-.558**	-
18. Handwriting Quality G4 <sup>a</sup>	-.015	-.236	-.086	.047	.059	.277	.530**	.591**	.695**	-.239	-.070	-.006	-.047	-.047	.194	-.351*	-.427**

Note. \* $p < .05$ . \*\* $p < .01$

<sup>a</sup> The correlations involving the handwriting quality scores should be interpreted keeping in mind that a high score refers to a high number of graphical errors, and a low score refers to good handwriting quality.

<sup>b</sup> Z-scores given by comparison to test norms were used for Chronosdictée and BHK

Table 3b

*Correlations Between Experimental and Control Measures of Spelling and Handwriting Abilities at the three Measurement Times in Cohort 2*

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Experimental single-word dictation task																	
1. Spelling Accuracy G3	-																
2. Spelling Accuracy G4	.840**	-															
3. Spelling Accuracy G5	.812**	.794**	-														
4. Handwriting Speed G3	.280*	.295*	.255	-													
5. Handwriting Speed G4	.159	.16	.264	.580**	-												
6. Handwriting Speed G5	-.109	-.042	.062	.529**	.686**	-											
7. Handwriting Quality G3 <sup>a</sup>	-.058	.113	-.029	.317*	.012	.115	-										
8. Handwriting Quality G4 <sup>a</sup>	.104	.148	.147	.236	.13	.228	.305*	-									
9. Handwriting Quality G5 <sup>a</sup>	-.299*	-.259	-.188	.145	.114	.410**	.455**	.443**	-								
Standardised spelling task (Chronosdictée) <sup>b</sup>																	
10. Spelling Accuracy G3	.782**	.758**	.746**	.277*	.259	.079	-.061	.071	-.265	-							
11. Spelling Accuracy G4	.753**	.733**	.701**	.19	.222	.037	.052	.097	-.254	.802**	-						
12. Spelling Accuracy G5	.729**	.730**	.702**	.178	.286*	.079	-.061	.078	-.239	.726**	.835**	-					
Standardised handwriting copying task (BHK) <sup>b</sup>																	
13. Handwriting Speed G3	.276*	.252	.26	.335*	.314*	.163	-.095	-.116	-.168	.379**	.353*	.336*	-				
14. Handwriting Speed G4	.274*	.163	.191	.105	.276*	-.032	.008	-.072	-.241	.299*	.333*	.437**	.622**	-			
15. Handwriting Speed G5	.531**	.505**	.518**	.146	.108	.047	.001	.101	-.123	.498**	.629**	.618**	.633**	.625**	-		
16. Handwriting Quality G3 <sup>a</sup>	-.219	-.078	-.177	.316*	.000	.188	.754**	.290*	.603**	-.142	-.112	-.203	-.104	-.193	-.147	-	
17. Handwriting Quality G4 <sup>a</sup>	-.142	-.109	.035	.034	.141	.206	.216	.549**	.365**	-.026	-.031	.006	-.190	-.041	.011	-.372**	-
18. Handwriting Quality G5 <sup>a</sup>	-.004	.143	.153	.228	.108	.358**	.467**	.482**	.474**	.043	.052	.057	-.098	-.230	-.004	-.691**	.447**

Note. \* $p < .05$ . \*\* $p < .01$

<sup>a</sup> The correlations involving the handwriting quality scores should be interpreted keeping in mind that a high score refers to a high number of graphical errors, and a low score refers to **good handwriting quality**.

<sup>b</sup> **Z-scores** given by comparison to test norms were used for Chronosdictée and BHK

Table 4

*Estimates of the Unconditional Linear Growth Curve Models for Spelling Accuracy, Handwriting Speed, and Handwriting Quality*

	Cohort 1			Cohort 2		
	Spelling	Speed	Quality	Spelling	Speed	Quality
	Estimate [95% BCI]	Estimate [95% BCI]	Estimate [95% BCI]	Estimate [95% BCI]	Estimate [95% BCI]	Estimate [95% BCI]
<b>Fixed effects</b>						
Intercept <sub>child</sub>	0.00 [0.00; 0.00]	1.34 [1.22; 1.46]	0.00 [0.00; 0.00]	0.00 [0.00; 0.00]	1.63 [1.48; 1.78]	0.00 [0.00; 0.00]
Slope <sub>child</sub>	0.84 [0.64; 1.04]*	0.35 [0.26; 0.44]*	0.06 [-0.03; 0.16]	0.63 [0.43; 0.80]*	0.16 [0.10; 0.23]*	0.04 [-0.04; 0.11]
<b>Random effects</b>						
Intercept <sub>child</sub>	0.32 [0.13; 0.65]*	0.09 [0.02; 0.18]*	0.11 [0.05; 0.21]*	0.62 [0.37; 1.05]*	0.17 [0.08; 0.30]*	0.06 [0.02; 0.13]*
Slope <sub>child</sub>	0.03 [0.00; 0.13]*	0.02 [0.00; 0.08]*	0.01 [0.00; 0.03]*	0.01 [0.00; 0.04]*	0.01 [0.00; 0.05]*	0.00 [0.00; 0.02]*
Intercept <sub>word</sub>	4.70 [2.79; 8.30]*	0.02 [0.01; 0.04]*	0.07 [0.04; 0.13]*	3.98 [2.40; 6.95]*	0.05 [0.03; 0.08]*	0.05 [0.02; 0.11]*
Slope <sub>word</sub>	0.03 [0.00; 0.16]*	0.01 [0.00; 0.01]*	0.00 [0.00; 0.01]*	0.07 [0.00; 0.24]*	0.00 [0.00; 0.00]*	0.00 [0.00; 0.01]*
Intercept <sub>residual</sub>	0.52 [0.13; 1.20]*	0.02 [0.01; 0.03]*	0.02 [0.00; 0.06]*	0.54 [0.21; 1.04]*	0.01 [0.01; 0.02]*	0.06 [0.03; 0.12]*
Slope <sub>residual</sub>	0.69 [0.30; 1.14]*	0.01 [0.01; 0.02]*	0.02 [0.00; 0.05]*	0.26 [0.07; 0.51]*	0.00 [0.00; 0.01]*	0.02 [0.00; 0.04]*
<i>PPP</i>	0.40	0.31	0.00	0.45	0.34	0.00
<i>DIC</i>	–	7050.80	–	–	5935.02	–
$R^2_{\text{child}}$	0.85	0.47	0.80	0.93	0.69	0.74
$R^2_{\text{word}}$	0.97	0.82	0.96	0.97	0.87	0.97
Number of words	40	40	40	40	40	40
Number of children	61	61	61	56	56	56
Number of observations	2440	2440	2440	2240	2240	2240
Number of parameters	17	20	66	17	20	66

*Note.* R-square averaged across time points. *PPP* = posterior predictive p-value.

*DIC* = deviance. BCI = Bayesian credibility interval.



Table 5

*Estimates of the Conditional Linear Growth Curve Models of Spelling, Handwriting Speed, and Handwriting Quality on Orthographic and Graphic Complexity in Cohort 1*

	Spelling Accuracy		Handwriting Speed		Handwriting Quality	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
<b>Fixed effects</b>						
Orthographic complexity	-3.97 [-4.92; -3.37]*	0.34 [-0.13; 0.83]	-0.06 [-0.17; 0.05]	-0.05 [-0.12; 0.02]	-0.15 [-0.33; 0.02]	-0.02 [-0.12; 0.07]
Graphic complexity	-0.92 [-1.42; -0.41]*	0.16 [-0.27; 0.42]	-0.04 [-0.17; 0.08]	-0.10 [-0.17; -0.03]*	0.35 [0.18; 0.54]*	0.00 [-0.10; 0.07]
Interaction	1.22 [0.11; 2.35]*	-0.33 [-0.79; 0.21]	-0.11 [-0.30; 0.15]	0.09 [-0.03; 0.23]	-0.06 [-0.40; 0.26]	-0.12 [-0.30; 0.07]
<b>Random effects</b>						
Orthographic complexity <sub>word</sub>	0.07 [0.00; 1.88]*	0.01 [0.00; 0.24]*	0.01 [0.00; 0.08]*	0.00 [0.00; 0.02]*	0.02 [0.00; 0.17]*	0.00 [0.00; 0.02]*
Graphic complexity <sub>word</sub>	0.12 [0.00; 1.88]*	0.01 [0.00; 0.29]*	0.01 [0.00; 0.07]*	0.00 [0.00; 0.02]*	0.02 [0.00; 0.17]*	0.00 [0.00; 0.02]*
Interaction <sub>word</sub>	0.20 [0.00; 7.11]*	0.02 [0.00; 0.92]*	0.01 [0.00; 0.07]*	0.01 [0.00; 0.07]*	0.04 [0.02; 0.65]*	0.01 [0.00; 0.07]*

*Note.* For handwriting quality scores, a high score refers to poor handwriting, and a low score refers to good quality.

Table 6

*Estimates of the Conditional Linear Growth Curve Models of Spelling, Handwriting Speed, and Handwriting Quality on Orthographic and Graphic Complexity in Cohort 2*

	Spelling Accuracy		Handwriting Speed		Handwriting Quality	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
Fixed effects						
Orthographic complexity	-3.54 [-4.25; -2.95]*	-0.28 [-0.08; 0.73]	-0.13 [-0.26; 0.00]	0.04 [-0.01; 0.09]	-0.11 [-0.29; 0.08]	-0.03 [-0.12; 0.06]
Graphic complexity	-0.45 [-1.11; 0.04]	0.18 [-0.13; 0.55]	-0.19 [-0.33; -.04]*	0.02 [-0.03; 0.06]	0.25 [0.03; 0.40]*	0.06 [-0.04; 0.15]
Interaction	0.65 [-0.35; 1.84]	-0.43 [-1.15; 0.17]	0.10 [-0.16; 0.36]	-0.01 [-0.11; 0.08]	-0.11 [-0.47; 0.27]	-0.02 [-0.18; 0.19]
Random effects						
Orthographic complexity <sub>word</sub>	0.11 [0.00; 2.20]*	0.02 [0.00; 0.46]*	0.01 [0.00; 0.13]*	0.00 [0.00; 0.01]*	0.03 [0.00; 0.19]*	0.00 [0.00; 0.02]*
Graphic complexity <sub>word</sub>	0.03 [0.00; 1.60]*	0.04 [0.00; 0.59]*	0.02 [0.00; 0.14]*	0.00 [0.00; 0.01]*	0.01 [0.00; 0.18]*	0.00 [0.00; 0.02]*
Interaction <sub>word</sub>	0.23 [0.00; 8.78]*	0.07 [0.00; 1.81]*	0.02 [0.02; 0.44]*	0.00 [0.00; 0.03]*	0.06 [0.01; 0.70]*	0.01 [0.00; 0.05]*

*Note.* For **handwriting quality** scores, a high score refers to poor handwriting, and a low score refers to good quality.

Table 7

*Correlation Coefficients at the Individual Level Between Growth Factors of Spelling, Handwriting Speed, and Handwriting Quality in Cohort 1 and Cohort 2*

		Spelling		Speed		Quality	
		Intercept	Slope	Intercept	Slope	Intercept	Slope
Spelling	Intercept	–	–.035	.156*	–.094*	–.003	–.037
	Slope	.000	–	.016	.014	.006	.002
Speed	Intercept	–.011	.010	–	–.024	.078*	–.011
	Slope	–.005	–.004	–.043*	–	–.010	.013
Quality	Intercept	–.020	–.031	.047	–.027	–	–.012
	Slope	–.032	–.002	–.010	.023	–.015	–

*Note.* Correlations for coh1 (Grades 2 to 4) are below the diagonal, and correlations for coh2 (Grades 3 to 5) are above the diagonal. For handwriting quality scores, a high score refers to poor handwriting, and a low score refers to good quality.

Appendix A. Average Performance at the Word-Dictation Task per Cohort according to Orthographic complexity: Orthographically Simple Words and Orthographically Difficult Words

	Cohort 1		Cohort 2	
	O simple	O difficult	O simple	O difficult
Spelling Accuracy (success rate)				
T1	71.8%	3.2%	88.5%	18.0%
T2	86.3%	14.2%	93.5%	32.3%
T3	88.9%	30.6%	94.1%	48.0%
Handwriting Speed (cm/s)				
T1	1.36 (0.52)	1.32 (0.55)	1.70 (0.63)	1.56 (0.66)
T2	1.78 (0.61)	1.63 (0.63)	1.74 (0.62)	1.66 (0.63)
T3	2.15 (0.79)	1.99 (0.76)	1.99 (0.68)	1.90 (0.73)
Handwriting Quality (number of graphic errors)				
T1	1.79 (0.97)	1.61 (0.95)	1.57 (0.88)	1.44 (0.84)
T2	1.58 (1.12)	1.37 (1.01)	1.28 (1.06)	1.16 (0.96)
T3	1.97 (1.11)	1.76 (1.07)	1.63 (0.98)	1.46 (0.85)

*Note.* Cohort 1: T1 = Grade 2; T2 = Grade 3; T3 = Grade 4, Cohort 2: T1 = Grade 3; T2 = Grade 4; T3 = Grade 5

DEVELOPMENT OF SPELLING AND HANDWRITING

Appendix B. Average Performance at the Word-Dictation Task per Cohort according to Graphic Complexity: Graphically Simple Words and Graphically Difficult Words

	Cohort 1		Cohort 2	
	G simple	G difficult	G simple	G difficult
Spelling Accuracy (success rate)				
T1	44.4%	30.6%	57.3%	49.2%
T2	55.5%	45.0%	65.4%	60.4%
T3	63.6%	56.0%	73.6%	68.6%
Handwriting Speed (cm/s)				
T1	1.34 (0.55)	1.34 (0.51)	1.73 (0.69)	1.52 (0.58)
T2	1.81 (0.65)	1.59 (0.57)	1.75 (0.66)	1.65 (0.59)
T3	2.18 (0.80)	1.96 (0.74)	2.04 (0.73)	1.85 (0.67)
Handwriting Quality (number of graphic errors)				
T1	1.52 (0.89)	1.89 (1.00)	1.36 (0.80)	1.65 (0.89)
T2	1.27 (0.99)	1.68 (1.11)	1.04 (0.93)	1.40 (1.06)
T3	1.65 (1.02)	2.08 (1.12)	1.36 (0.84)	1.73 (0.96)

Note. Cohort 1: T1 = Grade 2; T2 = Grade 3; T3 = Grade 4, Cohort 2: T1 = Grade 3; T2 = Grade 4; T3 = Grade 5