The development of handwriting speed and its relationship with graphic speed and spelling

Olivia Afonso[a*], Cristina Martínez-García[b], Fernando Cuetos[b], and Paz Suárez-Coalla[b],

[a]Department of Psychology, Health, & Professional Development, Faculty of Health & Life Sciences, Oxford Brookes University, Gipsy Lane, 0X3 0BP, Headington, Oxfordshire, United Kingdom

[b]Department of Psychology, Universidad de Oviedo, Plaza Feijóo, 33003, Oviedo, Spain

*** Corresponding Author Contact Information**

Olivia Afonso

Department of Psychology, Health, & Professional Development

Oxford Brookes University

Gipsy Lane OX3 0BP

Headington, Oxfordshire, United Kingdom

afonso.o@brookes.ac.uk

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Declarations of interest

None to declare.

Abstract

The present study addresses how handwriting speed increases with age among Spanish 8-, 10- and 12-year-old children (n = 60), and how this progression is related to spelling and more general graphic skills. Handwriting speed was measured in a spelling-to-dictation and a copying task, and graphic speed was measured in a trail tracing task. Results revealed that handwriting speed significantly increased from age 8 to 10 and remained stable up to 12 years of age, while graphic speed substantially increased only between 10 and 12 years of age. Thus, handwriting speed and graphic speed do not seem to follow the same pattern of development. Moreover, the relationship between linguistic processes and graphic skills with handwriting speed was not the same for all the groups. In the younger group, a different speed profile was obtained for each task, while in the groups of 10- and 12-year-olds, speed was similar in all the linguistic tasks. Graphic speed was positively correlated with speed in the spelling task only around the age of 10, and by age of 12 graphic speed correlated negatively when handwriting neatness was prioritized. Altogether, these results show that handwriting speed becomes consistent around the age of 10, when it is mostly affected by spelling ability and, in some circumstances, by graphic speed. By the age of 12, speed in linguistic tasks becomes decoupled from graphic speed and it is adapted depending on the relative importance of neatness and speed for the task.

Keywords: handwriting speed; spelling; graphic skills; handwriting development.

From primary school to higher education, students are expected to progress to be able to quickly produce written language. Particularly from secondary school, slow writers may struggle to record all relevant information during note taking or produce shorter texts than their peers in timed conditions such as exams (Connelly, Dockrell, & Barnett, 2005). Moreover, handwriting speed seems to affect not only the amount of text produced, but also its quality (Connelly et al., 2005; Connelly, Dockrell, Walter, & Critten, 2012; Graham, Berninger, Abbott, & Whitaker, 1997; Limpo, Alves, & Connelly, 2017; Puranik & Al Otaiba, 2012). This is thought to be especially true in the case of young children who have not yet automatized handwriting. For these children, the motors aspects of handwriting still exert considerable demands on working memory, leaving limited resources available to be devoted to higher-order levels of processing (Cameron, Cottone, Murrah, & Grissmer, 2016), such as planning or idea generation (Berninger & Amtmann, 2003). Thus, understanding how handwriting speed increases with age and the factors contributing to its development is of key importance to support the enhancement of writing skills in students of all ages.

One of the main difficulties in investigating the development of handwriting speed resides in the multidimensional nature of handwriting, which requires the integration of multiple cognitive and motor processes. Handwriting is a language skill, in part reliant on the acquisition and fast retrieval of accurate orthographic information. At the same time, it is a perceptual-motor ability, requiring the execution of precise hand-movements guided by the visual input provided by the produced letter shapes. In this sense, some of the abilities required to develop handwriting are shared with linguistic tasks such as reading (e.g., letter-sound knowledge), and some abilities are shared with other graphomotor skills without a linguistic component (e.g., painting and drawing; henceforth, graphic skills). This means that improvements in handwriting speed are likely to be linked not solely to the amount of handwriting practice, but also to the level of development of other abilities such as spelling or fine motor skills. Moreover, the integration of these different processes imposes considerable cognitive demands, especially before handwriting automaticity has been achieved and motor execution still requires considerable attentional resources (Cameron et al., 2016). In the present cross-sectional study, we explore the progression of handwriting speed between 8 to 12 years of age and the relationship between this evolution and the development of other relevant skills, namely spelling and graphic speed.

The existence of a close relationship between handwriting and spelling is explicitly recognized by the most influential models of handwriting (Kandel, Peereman, Grosjacques, & Fayol, 2011; Van Galen, 1991). Effects of spelling processes on the duration of handwriting movements have been reported in children as young as 5 years old (Fears & Lockman, 2018; Maldarelli, Kahrs, Hunt, & Lockman, 2015) and in adults beyond the age of 70 (Afonso, Álvarez, Martínez, & Cuetos, 2019). Spelling itself is a complex skill, including knowledge of the phonology-to-orthography conversion rules accepted in the language (referred to as the sublexical route) as well as the ability to store and retrieve from long-term memory whole-word orthographic representations (the lexical route). Recent experimental evidence has revealed that both spelling routes affect not only the ability to access or generate the orthographic form, but also the dynamics of the unfolding of the handwritten response (Afonso, Álvarez, & Kandel, 2015; Afonso, Suárez-Coalla, & Cuetos, 2015; 2020; Afonso, Suárez-Coalla, González-Martín, & Cuetos, 2018; Delattre, Bonin, & Barry, 2006; Kandel & Perret, 2015; Lambert, Alamargot, Larocque, & Caporossi, 2011; Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013; Sumner, Connelly, & Barnett, 2013; 2014). However, some evidence suggests that the impact of spelling on the mechanical aspects of handwriting may change throughout development.

Among the most studied sublexical variables, phonology-to-orthography consistency has been reported to affect writing durations in a group of 8-year-old Spanish children, but not in 10- or 12-year-olds (Suárez-Coalla, González-Martín, & Cuetos, 2018). The effect of word length on writing durations has also been observed to be stronger for 8-year-old than for 10-year-old children (Afonso et al., 2020). The impact of lexical variables on handwriting has also been reported to reduce throughout development. Afonso et al. (2018) reported that 8-year-old children produced the same sequence faster when it appeared in a high-frequency than in a low-frequency word. The effect was only marginally significant by the age of 10 and it was completely absent in a group of 12-year-olds. These authors proposed that spelling might reduce its impact on writing durations after the age of 10, once handwriting has become automatic. In line with the idea that a high degree of handwriting automaticity is achieved around this age, handwriting speed has been seen to increase from 8 to 10 years of age (Afonso et al., 2015; Afonso et al., 2020, González-Martín, Suárez-Coalla, Afonso, & Cuetos, 2017; Suárez-Coalla et al., 2018; Séraphin Thibon, Gerber, & Kandel, 2018) and to remain constant (Afonso et al., 2018; González-Martín et al., 2017; Pontart, Bidet-Ildei, Lambert, Morisset, Flouret, & Alamargot, 2013) or to reduce its increment (Graham, Weintraub, Berninger, & Schafer (1998) in older age groups. Although increases in handwriting speed have been reported after the age of 10 (Alves & Limpo, 2015; Chartrel & Vinter, 2006), it seems that around this point in development handwriting becomes an autonomous skill, relatively independent of spelling ability (Bosga-Stork, Bosga, Ellis, & Meulenbroek, 2016; Palmis, Danna, Velay, & Longcamp, 2017).

It is worth noting that the evidence summarized here has been obtained in languages with a variable degree of orthographic transparency. Spanish is a language with relatively consistent relations between phonemes and graphemes, while the French orthography is, in comparison, rather opaque. It seems that the effects of both lexical and sublexical variables on handwriting movements can be observed even in languages in which the high reliability of the sublexical route it is assumed to minimize the use that writers make of lexical spelling procedures (Jiménez & Muñetón-Ayala, 2002).

Comparatively less is known about the relationship that handwriting speed has with other graphomotor skills. It seems reasonable to assume that handwriting and graphic skills (such as painting, tracing or drawing) will affect each other throughout development, if only because they partially draw upon a similar set of abilities such as fine motor skills. Fine motor skills are known to contribute to handwriting skill (Hamstra-Bletz & Blöte, 1993; Tseng & Chow, 2000), and handwriting difficulties including poor legibility and increased writing times (Barnett, Henderson, Scheib, & Schulz, 2011; Prunty, Barnett, Wilmut, & Plumb, 2013; 2014), are frequent in children with Developmental Coordination Disorder. It is thus widely accepted by researchers and teachers that activities such as drawing, coloring or copying shapes are valuable in order to develop prerequisite skills for handwriting such as the ability to manipulate tools or basic stroke formation (Khalid, Yunus & Adnan, 2010). In line with this idea, common strategies are used in drawing and handwriting in children 6-7 years old (Tabatabaey-Mashadi, Sudirman, Khalid, & Lange-Küttner, 2015), and handwriting and drawing skills seem to be related in this age group (Khalid et al., 2010) and in older children (Bonoti, Vlachos, & Metallidou, 2005).

Moreover, drawing symbols has been reported to have some of the beneficial effects that have been associated with handwriting (Longcamp, Zerbato-Poudou, &

Velay, 2005). A body of behavioral and neuroscientific evidence suggests that from 4 to 6 years of age handwriting experience contributes to the ability to link visual processing and motor processes (James, 2010; 2017; James & Engelhardt, 2012; Vinci-Booher, James, & James, 2016), which would have a positive impact on reading development. Interestingly, it seems that visual-motor practice with any symbol (such as shapes or digits) may improve letter recognition (Zemlock, Vinci-Booher, & James, 2018) and increase handwriting speed (Vinter & Chartrel, 2010). This evidence has been interpreted to indicate that the production of other symbols leads to changes in the ability to integrate information from the visual and the motor systems similar to those associated to letter production. Thus, producing letters by hand and producing other graphic elements seem to share at least some underlying processes.

However, other findings suggest that handwriting speed may develop relatively independently from other hand skills, including graphic skills. Although differences were found in manual dexterity between a group of children with DCD and a group of children with dysgraphia, these were not associated to differences in handwriting speed (Prunty & Barnett, 2017). Several studies indicate that, although related, drawing practice and handwriting practice are not completely interchangeable. Limpo, Vigário, Rocha, and Graham (2020) recently reported that a transcription intervention improved handwriting fluency more than a drawing intervention in a group of children between 8-9 years of age. Reybroek & Michiels (2018) found that handwriting fluency but not the ability to draw loops and lines improved after a brief finger-writing treatment in a small group of children with Developmental Language Disorder. Adi-Japha and Freeman (2001) reported similarities between writing and drawing fluency until the age of 6, but kinematic differences between tasks were apparent from the age of 9. Thus, the relationship between handwriting and other motor skills might be restricted to specific tasks or might not be consistent throughout the development (Thomassen & Teulings, 1983).

In a study conducted with French children attending Grade 2 (around 8 years of age) and Grade 9 (around 15 years of age), Pontart et al. (2013) obtained evidence that suggests that the relevance for handwriting speed may shift from basic graphomotor skills to spelling knowledge at some point of development. In their study, children performed a spelling task, an alphabet writing task and a name writing task. Handwriting durations produced in name writing (a task assumed to assess low-level graphomotor skills) were correlated with handwriting durations in the spelling task in primary school children, but not in secondary school children. It was concluded that in the older group handwriting durations were mainly related to spelling processes, while in the younger group they were affected by both graphomotor constraints and reduced orthographic knowledge. Pontart et al. suggested that this change in the importance of graphomotor skills could be related to the automatization of handwriting. However, it is worth noting that in this study, when pen movement speed (instead of writing durations) was considered, a significant correlation between name writing and the spelling task was found also in secondary school pupils. Pauses during handwriting have been proposed to be greatly affected by linguistic processes (Afonso & Álvarez, 2019), so pen movement speed might be a more appropriate measure to investigate the relationship between graphic skills and handwriting speed than total writing durations.

In sum, it is still unclear to what extent changes in handwriting speed are associated to changes in graphic speed. It also remains to be seen if the importance of graphic skills for handwriting reduces to the benefit of spelling ability or if handwriting, once automatized, becomes relatively independent of other systems, including spelling and more general motor processes.

The present study

In this study, we assessed how handwriting speed evolves among a sample of Spanish children, aged 8, 10 and 12 years, and explored whether this evolution is related to changes in the influence of spelling processes and/or graphic speed. To investigate this issue, pen movement speed was measured in a spelling-to-dictation task, a copying tasks and a trail tracing task. The trail tracing task used here was introduced in a recent study exploring the relationship between handwriting speed and graphic motor skills in children with dyslexia (Martínez-García, Afonso, Cuetos, & Suárez-Coalla, 2020). In this previous study, children with dyslexia were slower than their peers of the same chronological age in this task, but equally fast than younger children with the same level of reading and spelling ability. Thus, this task seems to be suitable to detect developmental differences in graphic speed. The impact of both the lexical and the sublexical spelling routes on handwriting speed was assessed by manipulating, respectively, the lexicality (words, pseudowords) and the length of stimuli included in a spelling-to-dictation task. Although these variables are known to affect spelling processes (Henry, Beeson, Stark, & Rapcsak, 2007; Juul & Petersen, 2017), evidence for their influence on kinematic measures of handwriting is more reduced than that obtained for other psycholinguistic variables such as word frequency or phonology-to-orthography regularity. Based on previous evidence suggesting that sublexical variables affect handwriting movements more consistently than lexical variables (Afonso et al., 2018), we expect to find significant effects of word length on handwriting speed in this task, but it is less clear if lexicality will affect writing durations.

The sentence copying task and the trail tracing task (Martínez-García, et al., 2020) do not require the retrieval or generation of orthographic forms, so these tasks should provide measures of speed relatively unaffected by spelling knowledge. However, sentence copying, as the spelling-to-dictation task, demands the efficient retrieval and execution of letter shapes. This linguistic component is absent in the trail tracing task. If changes in handwriting speed in the dictation task are mainly related to the influence of spelling ability, speed in the copying tasks might follow a different pattern of development. By comparing the evolution of handwriting speed in the copying task and graphic speed in the trail tracing task we expected to determine the extent to which handwriting and graphic skills are related between 8-12 years of age. If there are developmental changes in the strength of the association between handwriting speed, spelling ability and graphic skills in this age range, correlations between pen speed among the different tasks should not be the same for the three groups. Namely, based on the limited evidence on this issue (Pontart et al., 2013), we expected graphic speed to be more related to handwriting speed in the younger groups (Age 8 and Age 10 group) than in the older group (Age 12).

Method

Participants

Sixty children (30 boys and 30 girls) were recruited from two primary schools in Asturias, Spain, to take part in the study. Twenty children were around 8 years old (M_{age} = 8;3, *SD* = 3 months), twenty were around 10 years old (M_{age} = 9;9, *SD* = 3 months) and twenty were around 12 years old (M_{age} = 11;9, *SD* = 3 months). In each age group, half of the children were boys and half were girls. The children 8-, 10-, and 12 years old attended Grade 2, Grade 4 and Grade 6, respectively. All were native Spanish speakers and attended schools located in areas of middle socio-economic status. All the participants had normal or corrected-to-normal vision and they did not have any known cognitive or motor impairment.

Materials and apparatus

For all the responses, the software Ductus (Guinet & Kandel, 2010) controlled stimuli presentation and digital recording of the handwritten responses. The three tasks were run on a HP Mini laptop. Participants were asked to perform each task with an Intuos Inking Pen on a piece of paper stuck to a WACOM Intuos 5 graphic tablet connected to the laptop.

Spelling-to-dictation task. A total of 48 stimuli, 24 words and 24 pseudowords, were selected to be included in the spelling-to-dictation task. For both words and pseudowords, half of the stimuli were short (two syllables, four letters) and half were long (3 syllables, 6-7 letters). Across short and long words, word frequency according to the values provided by ONESC (Martínez & García, 2008) was controlled (for short words, *M* = 131.96 and *SD* = 72.54; for long words, *M* = 134.37 and *SD* = 88.95). Pseudowords were created by swapping the first syllable of two experimental words of the same length[1]. For example, the pseudowords '***des**taña*' and '***mon**tino*' were created based on the target words '***des**tino*' (destiny) and '***mon**taña*' (mountain). Thus, the mean syllable frequency and length (in number of letters and syllables) were controlled across conditions. The full list of experimental stimuli is given in Appendix A. In addition, four stimuli (two words and two pseudowords) were used to serve as practice. Auditory

[1] In one pair of words (*manzana – sistema*), the two first syllables were swapped to create the pseudowords (*manzama – sistena*). This exception did not affect the relevant controls (mean syllable frequency and length).

stimuli for words and pseudowords were recorded by a female speaker using an H4n voice recorder with a microphone Ht2-P Audix and edited with Praat software.

Sentence copying task. A sentence including all the letters of the Spanish alphabet was selected to be copied in both versions (copy fast and copy best) of the task: *El niño exclama de alegría viendo al fabuloso periquito comer jugosos kiwis y zanahorias* (*The boy exclaims with joy watching how the fabulous parakeet eats juicy kiwis and carrots*).

Trail tracing task. Three different trail patterns (wave, loop and zigzag) were used in this task (Martínez-García et al., 2020). Two line-drawing pictures were placed at either end of each trail so they could be connected by drawing a continuous line within the trail boundaries, which were 1 centimeter apart (see Appendix B).

Procedure

The study design and procedure were approved by the Ethics Committee for Research of the Principality of Asturias, Spain. It was developed in accordance with the Declaration of Helsinki and the Spanish Law of Personal Data Protection (15/1999 and 3/2018) principles, and the data collection was covered by a written informed parental consent, obtained for all participants.

Children were tested individually in a quiet room at their school. All the participants performed the three tasks in the same order: spelling-to-dictation task, the tracing task and the sentence copying task. A whole experimental session lasted around 30 minutes.

Spelling-to-dictation task. In the spelling-to-dictation task, words and pseudowords were presented in different blocks via headphones. Half of the participants in each group started with the block of words and half started with the block of pseudowords. To counteract potential effects of the order in which stimuli were presented, four different lists per block were created. Children were asked to write each stimulus in lower case as quickly and accurately as possible on a different line on a lined sheet of paper placed over the digitizing tablet. Each trial started with the presentation of an auditory signal and a fixation point that remained on the screen for 500 milliseconds followed by the auditory presentation of the to-be-written stimulus. During the practice, children were instructed to hover the pen above the following line (i.e., the line placed just below their previous response). Then, the experimenter clicked on the left button of the mouse to present a new stimulus.

Sentence copying task. In this task, participants copied twice a sentence presented on a piece of paper situated above the right upper end of the tablet. Half of the participants of each group performed first the copy best task, while the other half performed the copy fast task first. Before starting each copy, the experimenter read the sentence aloud. In the copy best task, participants were instructed to copy the sentence in their best handwriting. In the copy fast task, they were asked to write as quickly as possible and accurately, but without worrying about the neatness of the handwriting.

Trail tracing task. The trails were printed on a sheet of paper and stuck on top of the digitizing tablet. Each child was instructed to follow each path with the pencil so as to join the two pictures presented at both ends of it. They were asked to do this as quickly as possible, without lifting the pen or pausing and without touching the boundaries of the path with the pencil. Recording of the response started as soon as the auditory signal was presented. Cronbach's alpha coefficient across the three trails was .83 (Martínez et al., 2020).

Statistical analysis

Analyses were conducted using R software (RStudio Team, 2015). For the analysis of accuracy in the spelling task, generalized mixed-effect model with a binomial distribution were used. A measure of pen movement speed (measured as the distance advanced by the pen divided by the time spent, expressed in cm/sec) was obtained for the spelling task, the sentence copying tasks, and the graphic task. In the spelling task, writing latencies (the time between the onset of the stimulus and the first contact of the pen with the digitizer) and accuracy were also analyzed. For kinematic measures obtained in the spelling and the copying tasks, ANOVAs were performed with mixed-effects analyses (Baayen, 2008). For each measure, stepwise model comparisons were conducted, and the one with the most complex adjustment but the lowest Bayesian information criterion (BIC) and significant χ^2 test for the log-likelihood was retained (Schwarz, 1978). F values from the ANOVAs of type III, with Satterthwaite approximation for degrees of freedom, are reported for fixed-effects and interactions. In the spelling task, ANOVAs on writing latencies and writing speed were performed with random intercepts for items and by-participants random slopes for the effect of lexicality, and age group (Age 8, Age 10, and Age 12), lexicality (words and pseudowords), and length (short and long) were fixed factors. Only correct responses were included in the analyses conducted on kinematic measures, so responses with misspellings, self-corrections or missing data were removed from these analyses (4.5%). For the sentence copying task, participants were introduced as a random-effect variable and age group and the type of task (copy fast and copy best) were fixed factors. For the graphic task, an ANOVA was conducted with age group and sex as between-subjects variables. For all the ANOVAs, if the main effect of age group or any of the interactions were significant, t-tests were performed, and the p-values were adjusted via the *Tukey* method. A p-value below .05 was adopted as a level of significance.

To further explore if the relationship between handwriting speed (as measured in in the spelling and the copying tasks) and graphic speed (as measured in the trail tracing task) changes throughout development, Pearson correlation coefficients among the measures of speed obtained in the different tasks were calculated separately for each age group.

Results

Spelling task

Accuracy analysis. A total of 134 errors were made in this task (49 in the Age 8 group, 43 in the Age 10 group, and 42 in the Age 12 group), which represents 4.5 % of all the responses. Across lexicality conditions, the errors were distributed as follows: 23 (.84 %) were made in words and 111 (4.06%) occurred in pseudowords. Across length conditions, 55 errors (2.01%) occurred in short stimuli and 79 (2.89%) occurred in long words. The analysis showed a significant effect of lexicality ($p < .001$; *Estimate*[2] = 1.83, $SE = 0.430$; $OR = 0.16$, $CI = .07\text{-}.37$), with fewer errors made in words than in pseudowords. The effects of length and age group were not significant, *t*s < 1.

[2] The estimates indicate differences in mean between groups or conditions compared in each contrast.

Writing latencies. Latencies referred to the time between the onset of the stimulus and the first contact of the pen with the digitizer and were measure in milliseconds. Means and standard deviations for writing latencies in each condition for each group are shown in Table 1. Means revealed that writing latencies decreased with age. They also showed that words were initiated faster than pseudowords and that short stimuli were initiated faster than long stimuli. Using the linear mixed-effects model fit by REML, we found that the best model (or lowest BIC) was: latencies ~ age group * lexicality * length + (1+lexicality|participant) + (1|item), $\chi^2(1) = 82.38$, $p < .001$. The main effect of age group was significant, $F(2, 57.02) = 12.05$, $p < 0.001$. Pairwise comparisons were significant between Age 8 and Age 10, t(57) = 3.02, $p = .010$, *Estimate* = 285, *SE* = 94.4, between Age 8 and Age 12, t(57) = 4.86, $p < .001$, *Estimate* = 459, *SE* = 94.4, but not between Age 10 and Age 12, t(57) = 1.84, $p = .165$, *Estimate* = 174, *SE* = 94.4. The lexicality effect, $F(1, 76.26) = 16.10$, $p < .001$, *Estimate* = 137, *SE* = 34.1, and the effect of length, $F(1, 43.48) = 5.52$, $p = .023$, *Estimate* = 59.2, *SE* = 25.2, were also significant. No other effects reached significance.

Table 1. *Mean writing latencies (in ms) and standard deviations (in parentheses) in the spelling-to-dictation task for each type of stimuli and for each age group.*

Lexicality	Length	Age 8	Age 10	Age 12
Words	Short	1445 (552)	1213 (383)	1018 (279)
	Long	1547 (634)	1214 (324)	1062 (289)
Pseudowords	Short	1575 (565)	1306 (428)	1147 (317)

	Long	1686 (628)	1383 (478)	1183 (372)

Writing speed. In this task, writing speed was measured as the distance advanced by the pen divided by the time spent in each word, expressed in cm/sec. Means and standard deviations for writing speed for each condition and group, as shown in Table 2, suggest that writing speed increased mainly between Age 8 and Age 10, but it was very similar for Age 10 and Age 12. The best model (or lowest BIC) was: speed ~ age group * lexicality * length + (1+lexicality|participant) + (1|item), ($\chi^2(1)$ = 544.22, p < .001). The effect of age group was significant, $F(2, 56.97) = 7.15$; p = .002. Children in Age 8 showed slower writing speed than children in Age 10, t(57) = 3.47, p = .003, *Estimate* = .76, *SE* = .22, and Age 12, t(57) = 3.03, p = .010, *Estimate* = .66, *SE* = .22. There was not a significant difference between the Age 10 and Age 12 groups, t(57) = 0.44, p = .898, *Estimate* = .10, *SE* = .22. No other effect was significant, but the interaction between word length and age group approached significance, $F(2, 2565.86) = 2.96$, p = .052. Pairwise comparisons conducted to explore this trend showed that differences in speed observed in long stimuli between Age 8 and Age 10, t(58.2) = 3.70, p = .006, *Estimate* = .81, *SE* = .22, and Age 8 and Age 12, t(58.2) = 3.17, p = .028, *Estimate* = .70, *SE* = .22, were larger than differences obtained in short stimuli between Age 8 and Age 10, t(58.1) = 3.21, p = .006, *Estimate* = .71, *SE* = .22, and between Age 8 and Age 12, t(58.2) = 2.87, p = .061, *Estimate* = .63, *SE* = .22.

Table 2. *Mean writing speed (in cm/sec) and standard deviations (in parentheses) in the spelling-to-dictation task of each type of stimuli and for each age group.*

Lexicality	Length	Age 8	Age 10	Age 12

Words	Short	2.71 (.63)	3.43 (1.14)	3.38 (.71)
	Long	2.68 (.57)	3.47 (1.11)	3.38 (.68)
Pseudowords	Short	2.65 (.55)	3.32 (1.08)	3.31 (.77)
	Long	2.55 (.47)	3.43 (1.05)	3.28 (.72)

Sentence copying task

Writing speed. In the copying task, writing speed was measured as the distance advanced by the pen divided by the time spent in each sentence, expressed in cm/sec. Means and standard deviations for writing speed in each type of task and group are shown in Table 3, revealing again an increase between Age 8 and 10 and a stabilization in Age 12. The best model (or lowest BIC) was: speed ~ age group * task + (1|participant), ($\chi^2(1) = 31.60$, $p < .001$). The main effect of age group was significant, $F(2, 56.85) = 11.66$; $p < .001$. Pairwise comparisons confirmed slower writing speed in the Age 8 group than in the Age 10 group, t(57.1) = 4.33, $p < .001$, *Estimate* = .857, *SE* = .20, and the Age 12 group, t(56.7) = 4.01, $p < .001$, *Estimate* = .79, *SE* = .20. The difference in speed between Age 10 ad Age 12 was not significant, t(57.1) = .33, p = .940, *Estimate* = .066, *SE* = .20. The effect of the type of copy task was also significant, $F(1, 94.24) = 45.76$; $p < .001$, *Estimate* = .821, *SE* = .07, with speed being higher in copy fast than in copy best.

Table 3. *Mean writing speed (in cm/sec) and standard deviations (in parentheses) in the sentence copying task for each type of task and each age group.*

Task	Age 8	Age 10	Age 12
Copy best	1.95 (.46)	2.81 (.78)	2.72 (.66)
Copy fast	2.76 (.49)	3.58 (.90)	3.57 (.74)

Trail tracing task

Writing speed. In the tracing task, writing speed was determined by measuring the distance advanced by the pen divided by the time spent in each trail (expressed in cm/sec). Separate ANOVAs were conducted for each tracing pattern (waves, loops and zigzag). The three ANOVAs showed the same pattern of results. Thus, only the results of analysis conducted on the average speed obtained across the three trails are discussed here. Means and standard deviations for speed in each group are shown in Table 4. We found a significant effect of age group, $F(2, 54) = 15.12$; $p < .001$, $MSE = 26.20$; $\eta_p^2 = .36$. Children in the Age 12 group were faster than children in Age 8, $t(19) = 4.96$, $p < .001$, and Age 10, $t(19) = 4.33$, $p < .001$. Speed was not significantly different between the Age 8 and Age 10 groups in this task, $t < 2$. The effect of sex was not significant.

Table 4. *Mean writing speed (in cm/sec) and standard deviations (in parentheses) in the trail tracing task for each grade.*

Age 8	Age 10	Age 12
3.13 (1.09)	3.61 (1.02)	5.31 (1.75)

Correlations among measures of writing speed

Correlation coefficients among the pen movement speed measured in the different tasks for the Age 8 group are shown in Table 5. For these children, the only significant correlation was between the copy best and the copy fast tasks. For the Age 10 group (see Table 6), writing speed in the spelling task was strongly and positively correlated with speed in both the copy best and the copy fast tasks, and moderately and positively correlated with speed in the graphic task. There was also a significant strong, positive correlation between both copying tasks. For the Age 12 group (see Table 7), the speed in the spelling task was strongly and positively correlated with speed in the copy fast task, and moderately and positively correlated with speed in the copy best task. Speed in the copy best task was moderately and negatively correlated with speed in the graphic task. No other correlation reached significance.

Table 5. *Pearson correlations among speed in writing tasks for Age 8.*

Tasks	1.	2.	3.	4.
1. Spelling	—			
2. Copy fast	.39	—		
3. Copy best	.25	$.62^{**}$	—	
4. Trails	.20	.19	.09	—

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Table 6. *Pearson correlations among speed in writing tasks for Age 10.*

Tasks	1.	2.	3.	4.
1. Spelling	—			
2. Copy fast	$.88^{***}$	—		
3. Copy best	$.84^{***}$	$.86^{***}$	—	

4. Trails	$.51^{*}$	.41	.42	—

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Table 7. *Pearson correlations among speed in writing tasks for Age 12.*

Tasks	1.	2.	3.	4.
1. Spelling	—			
2. Copy fast	$.75^{***}$	—		
3. Copy best	$.52^{*}$	.38	—	
4. Trails	.37	-.37	$-.63^{**}$	—

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Comparisons of the correlations found to be significant in more than one age group were calculated to establish if the strength of the correlations in speed across the different tasks was similar across groups. The positive correlation between the copy best and the copy task in Age 8 and Age 10 was significantly stronger in the older group, Z = 1.66, $p = .049$. The correlation between the speed in the spelling task and the copy best task was significantly stronger in Age 10 than in Age 12, Z = 1.88, $p = .030$. However, the correlations between the spelling task and the copy fast task in the two older age groups were not statistically different, Z = 1.17, $p = .120$.

Discussion

In the present study, we investigated if the relationship of handwriting speed with spelling processes and graphic skills changes throughout the course of development. Pen movement speed produced by typically developing Spanish children 8, 10, and 12 years of age was measured in three tasks which varied in their demands on linguistic processes. The spelling-to-dictation task required the explicit retrieval or generation of orthographic representations. The copy fast and the copy best tasks, respectively, also assessed the ability to quickly and accurately retrieve stored motor patterns for letters/graphemes but imposing a lesser burden on the spelling system. Speed in a simple graphic task (without any linguistic component) was measured in a trail tracing task. These sets of tasks allowed to obtain valuable information about the development of spelling, handwriting speed and graphic speed and the evolution of the interrelation between these skills between 8-12 years of age.

Development of spelling ability and its influence on handwriting speed

Results obtained in the spelling task revealed that 8-year-old children initiated and produced the written response more slowly than 10- and 12-year-old, which did not differ from each other. However, all children displayed similar levels of spelling accuracy. Altogether, this pattern of results seems to suggest that differences between second age groups and older children are linked to the ability to quickly start and execute the hand movements associated with writing, rather than to the ability to generate a correct orthographic form for the stimuli. This is in line with the fact that both lexicality and length affected latencies to a similar extent in the three age groups. Thus, participants seem to have used both lexical and sublexical spelling procedures to solve the task and, importantly, this was made in a similar fashion regardless of age. Interestingly, neither lexicality nor length affected writing speed. Thus, these variables do not seem to have a substantial impact on motor processes.

The absence of a lexicality effect coincides with previous observations suggesting that effects associated to the use of the lexical route on handwriting movements are limited, at least from the age of 9 or 10 (Afonso et al., 2018). Previous studies have reported significant effects on total writing durations of word frequency

(Afonso et al., 2018) and word length (Afonso, Suárez-Coalla, et al., 2015) in 8-year-old children and in adults, and of lexicality in adults (Roux et al., 2013). However, lexicality does not seem to affect durations when only on-paper handwriting speed (excluding pauses) are considered. It has been recently suggested that spelling processes affect writing durations not by directly affecting handwriting movements, but by increasing the duration of pauses (either between- or within-letter) between movement periods (Afonso & Álvarez, 2019). Thus, rather than occurring simultaneously, spelling and writing motor processes could alternate during production, at least in some circumstances (Olive, 2014). This would explain the pattern of results obtained in different studies, but more research needs to be conducted in order to clarify how linguistic and motor processes affect each other during writing. Further research should also clarify whether the substantial transparency of the relationship between phonemes and graphemes in Spanish might have led to an overreliance on the sublexical route for spelling and a reduction of the impact of lexical variables for children in the age groups tested here. Although lexicality did affect written latencies in our study, this variable might also affect writing durations in languages in which lexical processes have a stronger influence. Systematic crosslinguistic comparisons are needed to elucidate this issue.

Writing speed in the sentence copying task showed a similar pattern of development as that observed in the spelling task. Speed increased between age 8 and age 10 and remained stable between 10 and 12 years of age. This pattern replicates previous findings showing that Spanish children substantially increase their handwriting speed between 8 and 10 years of age, which then remains stable at least up to the age of 12 (Afonso, et al., 2018). This pattern was present whether children wrote as fast as possible or as neatly as possible.

Development of graphic speed

When graphic abilities aside from letter production were considered, a slightly different pattern of development was observed. Speed did not change between 8 and 10 years of age, but it dramatically increased between 10 and 12 years. It is unclear from our results to what extent improvements in graphomotor skills occur earlier than 8 years of age as well. Adi-Japha and Freeman (2001) found that the time that English children required to complete a drawing task decreased between ages 6 and 9, but Meulenbroek and van Galen (1986) did not find velocity to increase between children attending first and second grade in a task similar to that used in the present study. However, findings from the latter study cannot be easily generalized to the population to which children taking part in the present study belong. Children may have more experience nowadays with activities similar to the trail tracing task both at school and at home (e.g., in activity books) than they had 30 years ago. Differences in the amount of practice with this activity might also exist across countries. Thus, it is possible that children in our sample had experienced a period of substantial improvement of their graphic skills before the age of 8. In any case, our findings confirm that a reliable increase in graphic speed exists between 10 and 11 years of age. Thus, graphic speed and handwriting speed do not follow the same pattern of development.

Developmental changes in the importance of linguistic and graphic skills for handwriting speed

One of the most interesting findings of the present study is probably that handwriting speed seemed to have a different relationship with spelling processes and graphic skills in each group. For the younger group of children, pen movement speed was only significantly correlated between both versions of the copying task, suggesting that handwriting is not yet automatized in this group and that handwriting speed is strongly dependent on the specific conditions imposed by the task. However, for 10-year-old children, less variability in their performance across different writing tasks was found. This pattern is in line with the interpretation that the stabilization of speed between Age 10 and Age 12 in these tasks reflects the automatization of handwriting. By the age of 10, children were able to maintain a consistent speed profile across handwriting tasks. Interestingly, handwriting speed in the spelling task was also positively correlated with graphic speed at age 10. This may indicate that at this age handwriting draws upon spelling processes, but it also depends on more basic graphomotor skills (Pontart et al. 2013). However, it is important to note that handwriting speed measured in the copy tasks was not correlated with speed in the graphic task. More evidence is necessary to fully understand the significance of this pattern, but it might indicate that children in this age group only resort to a less automatic, more “drawing-like” way of writing when the task imposes significant demands in terms of spelling, such as in the dictation task. With less challenging tasks, such as copying a text, sufficient cognitive resources would be available and the handwriting system would not be affected by other related processes (Cameron et al., 2016).

In the Age 12 group, children who were faster in the graphic task took more time to complete the copy best task. This result suggests that graphic skills are becoming increasingly dissociated from handwriting skills. Graphic tasks may be relevant to develop visual-motor integration skills that would be fundamental during early handwriting acquisition (James, 2017). However, once automatized, handwriting speed seems to become uncoupled from more basic graphic skills. This result might be related to the absence of a significant correlation between both copying tasks in this group. It seems that by the age of 12 children do not perform the copy best task in the same way as they do the copy fast task. Although speed in the copy best and the spelling task were still correlated in this group, this correlation was stronger in Age 10. In contrast, the relationship between the copy fast and the spelling-to-dictation task remained similar across both age groups. Thus, there seems to be a change in the way that 12-year-old children perform the copy best task. This result warrants further investigation, but a tentative explanation for this pattern could be that, by this age, children with better graphic skills might be more aware of the trade-off between speed and accuracy in graphomotor tasks, so they might be better at prioritizing neatness over speed when they receive this instruction in the copy best task. The effective use of metacognitive strategies is known enhance writing skills (Cer, 2019), and this might be the case for handwriting ability as well. More evidence is necessary to assess this intriguing possibility.

Limitations

It is necessary to call attention to some limitations that may restrict the strength of the conclusions that can be extracted from the present findings. It is also possible that other variables not measured in the present study had a mediating role in the relationship between handwriting speed and graphic and spelling skills. For example, it has been proposed that reading ability could mediate the relationship between handwriting and motor abilities (Berninger, 2009; Julius, Meir, Shechter-Nissim, & Adi-Japha, 2016). A thorough cognitive profile of the children included in this study was not obtained, but children deemed by the teacher to have cognitive, motor or literacy difficulties were not included. In any case, all children attended school in the same region, with instructional practices and attainment criteria being the same in all of them. In fact, all children were recruited from only two different schools, so many attended the same class. Thus, we think that the variability that can be naturally expected in this age range in term of other skills is unlikely to have produced the specific pattern of results reported here.

The sample size of this study may be too small to have captured some true differences between groups in some of the tasks. This means that there may be differences in handwriting speed between Age 10 and Age 12, or in graphic speed between Age 8 and Age 10. However, our results confirm that the pattern of development of speed in these two types of tasks is not the same throughout childhood. Even if potential additional differences have not been detected, it is clear from our findings that the most striking increases in speed in the performance of linguistic and non-linguistic graphomotor tasks do not coincide in time. In the same vein, although some correlations could have reached significance with a larger sample size, the changes across groups in the relationship among tasks provide interesting information for future research and instructional practice.

Implications

The findings reported here have important implications for the development of cognitive models of handwriting. Although most models assume the multidimensional nature of the skill, little effort has been made to incorporate a developmental perspective to better describe the relationship between the different processes involved (linguistic, motor and attentional). The present study suggests that the importance of the association between these processes changes as a function of age, and this fact must be incorporated by future theoretical models. Implications can also be highlighted for how to enhance handwriting speed more effectively in different age groups. Practicing simple graphic tasks might be useful in early stages of the acquisition of the skill, but handwriting speed seems to evolve to become relatively independently of other graphomotor abilities. By the age of 10, a good level of graphic speed can contribute to increase handwriting speed in tasks that are particularly challenging in terms of linguistic processes (e.g., when spelling difficult words). But by the age of 12, handwriting speed seems to become considerably task-specific. Thus, for those children who, at this age, need to increase their handwriting speed to perform at the expected level, it might be advisable to use training activities as similar as possible as those in which they will be required to write at speed for academic progression.

Conclusion

In sum, the present findings show that Spanish children 8-12-year-old use both the lexical and the sublexical route to access orthographic representations in a spelling-to-dictation task, but that word length and lexical status have no influence on the speed of handwriting movements. Handwriting speed increases from 8 years of age, when it would still be considerably variable and dependent on the nature of the task, to around 10 years of age, when handwriting automaticity is achieved and a coherent profile of speed can be identified across different handwriting tasks. This profile seems to be relatively independent from more general graphic speed, although this seems to have some impact on tasks that impose higher cognitive demands in terms of spelling. By age 12, the handwriting speed profile becomes more nuanced and largely uncoupled from graphic skills. However, handwriting speed is still fairly stable within linguistic tasks requiring speeded production.

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Appendix A

Table A1. Stimuli used in the spelling-to-dictation task with English translations (in brackets) and lexical frequency for words.

Short			Long		
Pseudowords	Words	Word frequency	Pseudowords	Words	Word frequency
Dazo	Daño (*harm*)	211.17	Delanca	Defensa (*defense*)	66.19
Poño	Pozo (*well – water source*)	132.53	Pafensa	Palanca (*lever*)	49.96
Deña	Dedo (*finger*)	260.90	Destaña	Destino (*destiny*)	97.97
Ledo	Leña (*wood*)	71.81	Montino	Montaña (*mountain*)	377.15
Goro	Gota (*drop*)	79.60	Manzama	Manzana (*apple*)	102.54
Lota	Loro (*parrot*)	77.49	Sistena	Sistema (*system*)	188.64
Laza	Lana (*wool*)	108.05	Merdado	Mercado (*market*)	11.32
Tana	Taza (*cup*)	92.50	Solcado	Soldado (*soldier*)	72.83
Nuna	Nudo	79.40	Naquete	Naranja	105.84

	(*knot*)			(*orange*)	
Rado	Rana (*frog*)	132.27	Paranja	Paquete (*package*)	164.45
Pina	Pila (*battery*)	73.95	Pemate	Pelota (*ball*)	187.76
Zola	Zona (*zone*)	263.87	Tolota	Tomate (*tomato*)	87.86
	Mean	**131.96**		**Mean**	**134.38**

Appendix B

Trail tracing task