The impact of word frequency on peripheral processes during handwriting: A matter of age

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Abstract

Although several studies have found that the sublexical route of spelling has an effect on handwriting movements, the ability of lexical variables to modulate peripheral processes during writing is less clear. This study addresses the hypothesis that word frequency affects writing durations only during writing acquisition, and that at some point of development, the handwriting system becomes a relatively autonomous system unaffected by lexical variables. Spanish children attending Grade 2, 4, and 6 performed a spelling-to-dictation and a copy task in which word frequency was manipulated. Results revealed that written latencies decreased with age, especially between Grade 2 and 4 and also that writing durations decreased between these two groups. All these measures were longer during copying but the effect of task on written latencies and in-air pen trajectories was smaller for older children. Crucially, a significant word frequency effect on writing durations was observed only in Grade 2. This effect was marginally significant in Grade 4 and disappeared in Grade 6. However, all groups showed a similar effect of word frequency on written latencies. These findings suggest that lexical processes impact peripheral processes during writing acquisition and that this influence diminishes to eventually disappear at some point in development, presumably when the handwriting system becomes an autonomous system.

Keywords: handwriting, spelling, writing durations, word frequency, writing acquisition.

Handwriting is a complex skill that involves motor, perceptual and linguistic processes. However, little is yet known about how these processes interact with each other and how this relationship changes throughout development. Both learning to spell and handwriting impose great cognitive demands, but through constant practice during years of training handwriting becomes largely automatized and the spelling of a considerable number of words is learned. Although recent studies suggest that central processes (spelling) impact peripheral processes (handwriting), findings have been unclear about which linguistic variables may affect hand movements during writing production. Specifically, effects of word frequency have not been consistently observed, leading some authors to claim that lexical factors do not affect writing movements (Delattre, Bonin, & Barry, 2006) or that their influence is rather weak (Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013). In the present study we test the hypothesis that effects of word frequency on writing durations critically depend on the level of handwriting development.

According to Van Galen's model (1991), handwriting involves a series of hierarchically-ordered modules of processing, with higher-order modules including linguistic processes and lower-order modules involving motor processes. Linguistic modules deal with the retrieval and maintenance of the orthographic representation to be produced. Motor modules are oriented to execute the actual response and largely vary according to the requirements of the output modality. In handwriting, motor modules would include allograph selection, size control and muscular adjustment. Linguistic modules are usually referred to in the literature as *central* or *spelling processes* and motor processes are known as *peripheral* or *handwriting processes*. This distinction is almost undisputed and is supported by compelling evidence from neuropsychology and cognitive psychology (Ellis, 1979; Purcell, Turkeltaub, Eden, & Rapp, 2011; Weingarten, 2005).

Traditionally, studies addressing spelling processes have focused on analysis of the type and number of errors and, more recently, on analysis of written latencies (Afonso & Álvarez, 2011; Bonin & Fayol, 2002; Bonin, Laroche, & Perret, 2016; Bonin, Méot, Lagarrigue, & Roux, 2015; Bonin, Peereman, & Fayol, 2001). The analysis of kinematic variables such as writing duration or trajectory length was during many years restricted to the study of handwriting as a motor behaviour. This was mainly due to the idea that the orthographic representation must be retrieved before the response is initiated and the assumption that effects located at the central levels of processing should be observed before handwriting has started. However, over the last decade considerable evidence has been reported suggesting that central variables affect writing durations (Afonso, Álvarez, & Kandel, 2015; Afonso, Suárez-Coalla, & Cuetos, 2015; Delattre et al., 2006; Kandel, Álvarez, & Vallée, 2006; Kandel, Peereman, & Ghimenton, 2014; Kandel & Perret, 2015; Kandel & Valdois, 2005; Lambert, Alamargot, Larocque, & Caporossi, 2011). For example, different linguistic units have been observed to modulate hand movements during writing. Inter-letter interval durations have been found to be sensitive to the position of syllable boundaries (Álvarez, Cottrell, & Afonso, 2009; Kandel et al., 2006) and morphological boundaries (Kandel, Álvarez, & Vallée, 2008; Kandel, Spinelli, Tremblay, Guerassimovitch, & Álvarez, 2012). The presence of complex graphemes (Kandel & Spinelli, 2010) or double letters (Kandel et al., 2014) is known to affect letter durations. More recently, some studies have been conducted to determine whether the main mechanisms available to access orthographic representations during spelling have a substantial impact on peripheral processes (Kandel & Perret, 2015; Roux et al., 2013).

There is extensive agreement about the fact that spelling may be achieved through at least two different routes. In the so-called lexical route, whole-word orthographic forms are retrieved from the *orthographic output lexicon*, a long-term memory system in which known words are stored. These lexical representations are thought to be stored according to their frequency in the language, so high-frequency words are more easily accessed than low-frequency words (Bonin et al., 2016). The sublexical route applies the phonology-to-orthography (PO) conversion rules permitted by the language. This route is especially useful when spelling unknown words or nonwords, although there is abundant evidence of the use of the sublexical route also during word writing (Afonso & Álvarez, 2011; Afonso, Álvarez, et al., 2015; Afonso, Suárez-Coalla, et al., 2015; Bonin et al., 2015; Bonin et al., 2001). In fact, effects of PO regularity (Delattre et al., 2006; Kandel & Perret, 2015; Kandel & Valdois, 2005; Lambert et al., 2011; Roux et al., 2013) and PO consistency (Afonso, Suárez-Coalla, et al., 2015) have repeatedly been observed to affect writing durations. In their study, Kandel and Valdois (2005) found that French children attending Grade 1 and Grade 2 produced longer writing durations in irregular than in regular words. Significant effects of PO regularity on writing durations have also been observed in adults (Delattre et al., 2006; Lambert et al., 2011; Roux et al., 2013). It is worth mentioning that different measures of were used in these studies. While Kandel and Valdois and Roux and colleagues reported mean stroke durations, Lambert and colleagues reported whole-word durations. Despite this difference, evidence from these studies is consistent with the idea that the sublexical route has a considerable impact on peripheral processes during handwriting. However, previous studies have been less consistent when the influence of the lexical route on writing durations has been put to test.

Although Delattre et al. (2006) observed a significant effect of PO regularity in written latencies and writing durations in a spelling-to-dictation task, word frequency affected only written latencies. The same pattern of results was observed by Lambert et al. (2011) when the same variables were tested in a copying task. Conversely, other studies have found effects of lexical variables (namely, lexicality and lexical frequency) in the duration of writing movements. Roux et al. (2013) obtained a significant effect of lexicality on writing durations but the effect largely varied as a function of the position of the letter being measured. Writing durations for pseudo-words compared to words were longer in the initial letters but shorter in the final positions. In an early study, Søvik, Arntzen, Samuelstuen, and Heggberget (1994) found that 9 year-old children produced longer writing durations for long low-frequency words than for long high-frequency words. More recently, Kandel and Perret (2015) observed that writing durations in children between 8-10 years of age were affected by word frequency, although this effect only appeared in the letters located at the third position. In sum, previous evidence seems to confirm that sublexical procedures affect handwriting processes. However, whether or not lexical processes may have an effect on peripheral processes during handwriting is a question that remains unsolved.

One reason that might explain the discrepancies among previous findings is the age of the participants tested in those studies. It is worth noting that studies investigating this issue with children have revealed significant effects of word frequency on writing durations (Kandel & Perret, 2015; Søvik et al., 1994), meanwhile studies conducted with adults have not (Delattre et al., 2006; Lambert et al., 2011). Bosga-Stork, Bosga, Ellis, and Meulenbroek (2016) found in a recent longitudinal study that handwriting speed had a significant positive correlation with spelling in Grade 1 and 2, but not in Grade 3. These authors proposed that handwriting may develop as an autonomous skill in Grade 3 (around 9-10 years old), thus becoming fairly independent of other cognitive skills, including spelling. If handwriting becomes independent of spelling at some point during the development, it seems reasonable to think that central processes may have a decreasing impact on motor processes. A similar claim has been made by Kandel and Perret (2015) to account for their finding that the PO regularity effect diminished with age. In a study with Spanish adult participants, Afonso et al. (2015) obtained a significant difference between high- and low-frequency words in whole-word writing durations, but this effect vanished when only the in-air pen durations were considered. The authors claimed that the effect of word frequency on whole-word durations might have been due to differences in the identity of the letters measured. Thus, they could not conclude whether this effect occurred as a result of central or peripheral factors. When a similar procedure was used with 8-12 year old children, word frequency effects were observed in both whole-word writing durations and in-air pen durations (Afonso, Suárez-Coalla, & Cuetos, submitted). Although these findings may be attributed to the comparison of different letters, they seem to concur with the idea that lexical variables may affect hand-movements during writing acquisition, but only until handwriting acquires a relative independence from other linguistic systems.

In the present study, we address this question by analysing a range of online measures of the written response produced by Spanish children attending Grade 2, Grade 4 and Grade 6 in the context of two different tasks: a spelling-to-dictation and a direct copying transcoding task. We measured only the first two letters of the words, which were mostly the same in both conditions. In this way, we minimize the impact of the identity of the specific letters being measured. We selected children from grades separated by two years to maximize our chances of observing a change in the impact of word frequency on writing durations as a consequence of the development of handwriting abilities. In their study, Kandel and Perret (2015) obtained a similar effect of word frequency on writing durations in children of 8, 9 and 10 years of age. Furthermore, no significant differences were found between 9 and 10 year old-children in writing durations. According to these results, if handwriting actually becomes an independent system as a consequence of a substantial increase in handwriting speed (Bosga-Stork et al., 2016), this must happen later in development. For this reason, children recruited for this experiment ranged between 7 and 12 years of age. Measures of written latencies, writing durations and in-air pen trajectories corresponding to the first two letters are reported here. Recent studies have found that the length of the trajectory traced by the pen in the air during handwriting is also sensitive to linguistic aspects, at least in children (Afonso et al., submitted; Nottbusch, 2015). In this study, we hope to provide more information about the variables that may affect this scarcely-explored measure.

Method

Participants

Sixty typically-developing children (29 males and 31 females) between 7 and 12 years of age participated in this study. 20 children (10 males, 10 females) attended Grade 2 (mean = 7 years and 8 months; SD = 2.91 months), 20 children (9 males, 11 females) attended Grade 4 (mean age = 9 years and 8 months; SD = 3.98 months) and 20 children (10 males, 10 females) attended Grade 6 (mean = 11 years and 8 months; SD = 3.24 months). They were all native Spanish speakers and had no known motor or perceptual disorders. Participants were recruited from two schools in the Oviedo urban area. None of them had repeated or skipped a grade, and their school attendance was regular. Parental written consent was collected for all participants.

Material

Twenty Spanish words were selected as experimental stimuli. 10 words were high-frequency words (e. g., SOLDADO, soldier) and 10 were low-frequency words (SOLFEO, sol-fa). According to the values provided by BuscaPalabras (Davis & Perea, 2005), high-frequency words had a mean frequency of 39.86 (SD = 40.19) per million, and low-frequency words had a mean frequency of 1.54 (SD = 1.27) per million. Across conditions, words were matched in the identity of the first two letters (except in 4 pairs in which only the first letter was matched), and controlled by word length (number of letters and syllables), structure of first syllable, and orthographic neighbourhood. Only words with consistent phonology-to-orthography correspondences were selected. The full set of experimental stimuli with the values for word frequency and controlled variables is given in Appendix A. For each word, a visual and an auditory stimulus were created for the direct copy transcoding and the spelling-to-dictation task respectively. The mean acoustic duration of high frequency and low frequency words was controlled, with durations of 750 and 757 ms respectively. Twenty additional words were selected as fillers and three additional words were selected to serve as practice.

Apparatus

Stimuli presentation and digital recording of the responses were controlled by Ductus (Guinet & Kandel, 2010). The experiment was run on an HP Mini laptop. A WACOM Intuos 5 graphic tablet connected to the computer and an Intuos Inking Pen were used to register the participants' responses. Auditory stimuli were recorded by a female speaker with a Plantronics microphone and edited with Audacity to start at the beginning of the waveform.

Procedure

The procedure of this experiment was approved by the Ethics Committee of the Faculty of Psychology of the University of Oviedo. The experimental sessions were conducted for each participant individually in a quiet room in the school. For all the participants the spelling-to-dictation task was conducted before the direct copy transcoding task. We chose this method instead of counterbalancing the administration of the tasks to avoid some children (those children performing the copy task in the first place) being exposed to the orthographic representations of the words before performing the spelling-to-dictation task.

In the spelling-to-dictation task, each trial started with the simultaneous presentation of an auditory signal and a 500-millisecond fixation point. The auditory stimulus was presented 1000 milliseconds after the offset of the fixation point. Participants had to write the word in lower case on a lined sheet of paper placed over the digitizer as quickly and as accurately as possible. When they finished a response, participants were instructed to hold the pen over the next line of the response sheet, but without making any contact with the paper. Then the experimenter clicked the left button of the mouse to start a new stimulus. In the direct copy transcoding task, a trial started with the same auditory signal and fixation point as in the spelling-to-dictation task, and was followed by a 1000-milisecond white screen. The visual stimulus was then presented in black upper-case Calibri 60 point font on a white background and remained onscreen until the next trial started. The instructions given to the participants were the same as in the spelling-to-dictation task. Their attention was called to the fact that they had to write the words in lower case in spite of the fact that they would see the stimulus in upper case. The experiment lasted around 35 minutes.

Statistical analysis

The statistical analyses were conducted on written latencies, critical segment duration and in-air pen trajectories. ANOVAs were run with mixed-effects analyses (Baayen, 2008) using R-software (RStudio, RStudio Team, 2015) with participants, items and first bigram as random-effect variables and grade, word frequency and task as fixed-effect variables. The most complex adjustment model (adjustment on the by-participants and by-item intercepts and by-participant slopes) was included in all the analyses (Barr, Levy, Scheepers, & Tily, 2013). Stepwise model comparisons were conducted from the most complex to the simplest model and the one with the most complex adjustment but the smallest BIC (Schwarz, 1978) and significant χ^2 test for the log-likelihood was retained.

Results

Written latencies

Written latencies were defined as the time between the onset of the stimulus and the occurrence of the first contact of the pen with the digitizing tablet. Table 1 shows the means and standard deviations for written latencies in each condition for the three groups. The main effect of group was significant, $F(2, 56.96) = 34.84$; $p < .001$. *T*-tests revealed that children in Grade 2 required more time to initiate the written response than children in Grade 4, $t(37.98) = 5.52$, $p < .001$, and Grade 6, $t(34.42) = 8.52$, $p < .001$. Moreover, children in Grade 4 produced longer latencies than children in Grade 6, $t(34.02) = 2.07$, $p < .05$. To obtain further information about the group effect, t-tests were conducted on the computation of the differences in written latencies between one group and the next (Grade 2 – Grade 4 and Grade 4 – Grade 6). This analysis will allow us to determine whether written latencies are especially shortened in a specific period during these years. Results revealed that differences were larger between Grades 2 and 4 than between Grades 4 and 6, $t(36.41) = 3.58$, $p < .001$. The main effect of task was also significant, $F(1, 56.91) = 50.07$; $p < .001$. Written latencies were longer in the direct copying transcoding task than in the spelling-to-dictation task. The interaction between the type of task and the group was significant, $F(2, 56.91) = 5.74$; $p < .01$. All the groups initiated the responses significantly faster in spelling-to-dictation than in the direct copy transcoding task, $t(19) = 5.64$, $p < .001$ for Grade 2, $t(19) = 2.88$, $p < .01$ for Grade 4, and $t(19) = 3.22$, $p < .005$ for Grade 6. T-tests conducted on the differences in written latencies between tasks (direct copy transcoding - spelling-to-dictation) showed a larger effect of task in Grade 2 than in Grade 4, $t(35.78) = 2.69$, $p < .05$, and Grade 6, $t(33.59) = 2.83$, $p < .01$. There was not a significant difference between Grades 4 and 6 in the size of task effect, $t < 1$. The interaction Type of task x Word frequency was also significant, $F(1, 64.06) = 10.18$; $p < .005$. Word frequency significantly affected written latencies in the copy task, $t(59) = 5.01$, $p < .001$, but not in the spelling-to-dictation task, $t < 1$.

(Table 1 about here)

Critical segment durations

Critical segment durations refer to the time between the first contact of the pen with the digitizer in a given word and the beginning of the third letter of that word. The trajectory and tangential velocity were used to isolate the critical segment using geometric (cuspids and curvature maxima) and kinematic (velocity minima) criteria, as proposed by Kandel and Valdois (2006). Table 2 shows the mean durations and standard deviations for critical segment durations for each condition and group. The effect of group was significant, $F(2, 56.97) = 33.35$; $p < .001$. Children in Grade 2 spent more time writing the critical segment than children in Grade 4, $t(24) = 5.87$, $p < .001$, and Grade 6, $t(25.52) = 6.38$, $p < .001$. However, children in Grade 4 and Grade 6 wrote the critical segment equally faster, $t = 1.2$. The main effects of type of task, $F(1, 56.79) = 27.37$; $p < .001$, was also significant. Critical segments were produced faster in the direct copy transcoding task than in the spelling-to-dictation task. Word frequency interacted with group, $F(2, 315.01) = 4.58$; $p < .05$. *T*-tests revealed that word frequency significantly affected segment durations in Grade 2, $t(19) = 3.17$, $p < .01$, and marginally in Grade 4, $t(19) = 1.9$, $p = .07$. No effect of word frequency was observed in Grade 6, $t = 1.3$.

(Table 2 about here)

In-air pen trajectories

In-air pen trajectories were measured as the total length (in millimetres) of the trajectory drawn by the pen in the absence of contact with the tablet within the critical segment. Table 3 shows mean in-air pen trajectories for each condition and group. The effect of task was significant, $F(1, 2324.2) = 7.72$; $p < .01$. Shorter in-air pen trajectories were produced in spelling-to-dictation than in direct copy transcoding. The type of task significantly interacted with group, $F(2, 2324.2) = 3.51$; $p < .05$. Increased in-air pen trajectories in direct copying transcoding compared to spelling-to-dictation were observed in Grade 2, $t(19) = 3.02$, $p < .01$, but not in Grade 4 or 6, all *t*s < 2.

(Table 3 about here)

Discussion

In the present study, we aimed to test how the relation between central and peripheral processes evolves throughout the development of the writing skill. Specifically, we investigated the impact of word frequency on handwriting movements, as a reflection of the influence of the lexical route of spelling on motor processes during handwriting. Spanish children attending Grades 2, 4 and 6 performed a direct copy transcoding task and a spelling-to-dictation task in which word frequency was manipulated. Results showed that written latencies decreased from Grade 2 to Grade 6, with larger differences between Grades 2 and 4 than between Grades 4 and 6. Writing durations were longer in Grade 2 and did not differ between Grade 4 and 6. Word frequency significantly affected written latencies in the copying task. Crucially, the word frequency effect observed in writing durations largely depended on the group. High-frequency words were written significantly faster than low-frequency words in Grades 2. This effect was only marginally in Grade 4 and was absent in

Grade 6. These results support the hypothesis that word frequency affects writing durations in children around 8 years of age and that this influence seems to gradually decrease and eventually disappears. Children by the age of 12 no longer showed a significant effect of word frequency in writing durations but only in written latencies. Thus, children in Grade 6 showed a pattern of results similar to that reported in studies conducted with adults. In order to estimate the degree of confidence in this null finding we calculated the Bayes factor for this result. The Bayes factor was .53, indicating that the null-hypothesis is more likely than the alternative hypothesis in this contrast. This value is above the .33 threshold conventionally associated to "substantial support for the null hypothesis" (Lee & Wagenmakers, 2014), and thus considered inconclusive. In any case, our findings are in line with the idea that the influence of lexical processes on peripheral processes is reduced with the development of handwriting skill and suggest that lexical variables have a detectable effect on writing movements only during writing acquisition.

As suggested by Bosga-Stork et al. (2016), once handwriting abilities have reached a certain level of development, handwriting seems to become an autonomous system, relatively independent of the spelling system. Although the progressive decrease of the impact of word frequency may be related with the parallel increase in handwriting speed, this may not be the only factor responsible for the independence of the handwriting system. Children in Grade 4 did not show longer writing durations than children in Grade 6 but the former group showed a small (marginally significant) word frequency effect on writing durations. This finding might indicate that the functional separation between lexical processes and peripheral processes is not only due to an increase in handwriting speed.

Some differences can be highlighted between the present and previous studies. Bosga-Stork et al. proposed that the handwriting system was already independent from spelling in Grade 3. In their study, Kandel & Perret (2015) did not show differences in the size of the word frequency effect between groups of children aged 8, 9, and 10 years old. Although we detected a significant word frequency effect on writing durations in Grade 2, children continued to show some sensitivity to word frequency on writing durations around 10 years of age (Grade 4). Only writing durations produced by older children (around 12 years old) seemed to be unaffected by word frequency, resembling the results observed in previous studies with adults. These differences between studies could be due to differences in the handwriting skills of the children participating in these studies, specific policies about teaching handwriting or some properties of the languages used (Dutch, French and Spanish). More research is necessary to clarify the factors that may modulate the precise age at which handwriting becomes independent of lexical information. It is important to notice that word frequency had a similar effect on written latencies in all the groups and that this effect was similar regardless of the age. Word frequency effects on written latencies have repeatedly been obtained in adults (Afonso, Suárez-Coalla, et al., 2015; Bonin & Fayol, 2002; Bonin et al., 2016; Bonin et al., 2015; Bonin et al., 2001; Delattre et al., 2006; Lambert et al., 2011). It seems that during these years of development, word frequency consistently affects the access to the orthographic representation before the initiation of the written response. However, the impact of word frequency on motor modules varies throughout development. It is unclear from our data whether the word frequency effect observed in writing durations is due to the persistence of the word frequency effect observed in latencies, or to the fact that the retrieval of the motor patterns of handwriting is sensitive to word frequency in early years of acquisition. Moreover, written latencies were affected by word frequency only in the copy task. Thus, this effect might be related to reading and not to writing processes. In other words, it cannot be concluded from our findings whether or not the locus of both word frequency effects (on written latencies and on writing durations) obtained in younger children is the same. Nevertheless, the fact that the effect on written latencies appeared only during copy but the effect on durations did not interact with the type of task may suggest that they stem from different processes. In any case, it seems that once handwriting has been mastered, motor modules are no longer affected by word frequency.

However, the claim that handwriting evolves to become an independent system does not imply that writing durations are insensitive to linguistic variables. Sublexical processes seem to have a consistent impact on peripheral processes. Nonetheless, it seems that after a certain level of handwriting skill has been achieved, lexical access to an orthographic representation only influences the spelling processes. It is possible that the handwriting system becomes more atomised and starts to deal with sublexical units rather than with lexical units. This would increase the efficiency of the system, which would store motor patterns for a limited number of small units that could be assembled to produce a large number of known or unknown words. Some evidence suggests that this can be especially true in the case of Spanish-speaking children. Kandel and Valdois (2006) reported that Spanish children seemed to copy words as whole orthographic units. In contrast, French-speaking children produced the written response according to syllable-sized units. In line with this evidence, our findings may be a consequence of a tendency to use smaller units for programming the motor response in later stages of handwriting development.

The task effect also suggests a progression towards achieving a more adult-like pattern in children in Grade 6. Previous studies have shown that adults produce longer written latencies (Afonso, Suárez-Coalla, et al., 2015; Bonin et al., 2015) and in-air pen durations (Afonso, Suárez-Coalla, et al., 2015) in copying than in spelling-to-dictation. In the present study, children in Grade 2 produced shorter written latencies and in-air pen trajectories in the copying task than in spelling-to-dictation; children in Grade 4 and 6 produced longer written latencies in the copying than in the spelling-to-dictation task (although this effect was larger in Grade 2) and similar in-air trajectories in both tasks. The pattern observed in written latencies is likely to be related to the fact that younger children require more time to read the visually presented words than older children. As children increase their reading speed they require less time to start writing in this task. This pattern is consistent with a tendency towards the adult pattern of longer times in spelling-to-dictation. The fact that in-air pen trajectories were sensitive to the type of task in Grade 2 but not in older children might be indicating a higher influence of lexical aspects during writing at this age. On the other hand, this effect may be related with children in Grade 2 looking back to the visually-presented stimulus to refresh the orthographic representation. More research is necessary to establish the origin of effects observed in in-air pen trajectories in younger children.

In sum, our study confirms that central variables impact peripheral processes during handwriting. Namely, we observed that word frequency impacted writing durations in younger children. However, this influence decreased with the development of handwriting skill. In Grade 4, the influence of word frequency on writing durations was only marginally significant and disappeared by Grade 6. Our findings make a valuable contribution to both cognitive models of writing production and to research on handwriting and spelling development. An important point for the cognitive study of writing production is that, although PO regularity and consistency have repeatedly been observed to affect writing durations, word frequency seems to modulate hand movements only during writing acquisition. Any theoretical model of writing should account for the fact that different central processes do not have the same impact on peripheral processes. From a developmental perspective, our findings suggest that handwriting may become an autonomous skill relatively independent of the information stored in the lexicon around 11 years of age.

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Appendix A

Experimental stimuli used in the spelling-to-dictation task and the direct copying transcoding task.

	WF	NL	NS	*N*
HF				
Menor	128.04	5	2	3
Mente	72.32	5	2	4
Respeto	60.54	7	3	0
Resumen	11.79	7	3	0
Senador	5	7	3	2
Sendero	10	7	3	1
Soledad	62.5	7	3	0
Soldado	23.93	7	3	2
Torero	5.36	6	3	1
Torneo	19.11	6	3	1
Mean	**39.86**	**6.40**	**2.80**	**1.40**
LF				
Molinero	0.18	8	4	0
Moldeado	1.61	8	4	1
Rasante	1.61	7	3	1
Raspado	0.18	7	3	2
Serial	2.14	6	2	1
Sermón	3.57	6	2	0
Solera	2.5	6	3	5
Solfeo	0.18	6	3	0
Toril	0.36	5	2	0
Torta	3.04	5	2	8
Mean	**1.54**	**6.40**	**2.80**	**1.80**

WF = Word frequency; NL = Number of letters; NS = Number of syllables; *N* = Orthographic neighbourhood; *HF* = High-frequency words; *LF* = Low-frequency words.

Table 1

Table 1. Mean written latencies (in milliseconds) and standard deviations (in parentheses) for each condition of children in Grade 2, Grade 4 and Grade 6.

	Grade 2		**Grade 4**		**Grade 6**	
	Spelling-to-dictation	**Direct copy transcoding**	**Spelling-to-dictation**	**Direct copy transcoding**	**Spelling-to-dictation**	**Direct copy transcoding**
High-frequency	1437 (314)	2154 (657)	1198 (243)	1471 (574)	1065 (203)	1327 (427)
Low-frequency	1448 (379)	2313 (709)	1222 (285)	1592 (573)	1072 (204)	1406 (536)

Table 2

Table 2. Mean writing durations (in milliseconds) for the critical segment (first two letters) and standard deviations (in parentheses) for each condition of children in Grade 2, Grade 4 and Grade 6.

	Grade 2		**Grade 4**		**Grade 6**	
	Spelling-to-dictation	**Direct copy transcoding**	**Spelling-to-dictation**	**Direct copy transcoding**	**Spelling-to-dictation**	**Direct copy transcoding**
High-frequency	1115 (340)	1037 (422)	717 (192)	648 (160)	664 (174)	625 (160)
Low-frequency	1171 (390)	1067 (363)	737 (194)	664 (144)	682 (167)	642 (145)

Table 3

Table 3. Mean in-air pen trajectories (in millimetres) and standard deviations (in parentheses) for each condition of children in Grade 2, Grade 4 and Grade 6.

	Grade 2		**Grade 4**		**Grade 6**	
	Spelling-to-dictation	**Direct copy transcoding**	**Spelling-to-dictation**	**Direct copy transcoding**	**Spelling-to-dictation**	**Direct copy transcoding**
High-frequency	2.25 (.21)	5.72 (.60)	1.89 (.11)	1.78 (.13)	1.73 (.08)	1.60 (.07)
Low-frequency	2.56 (.24)	6.96 (.71)	1.84 (.10)	1.83 (.12)	1.75 (.08)	1.64 (.08)