Cognition 136 (2015) 325–336

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

How does the interaction between spelling and motor processes build up during writing acquisition?

Sonia Kandel [a,b,c,*], Cyril Perret [d]

[a] Univ. Grenoble Alpes, LPNC (CNRS UMR 5105) – BP 47, 38040 Grenoble Cedex 9, France
[b] Institut Universitaire de France, 103 bd Saint Michel, 75005 Paris, France
[c] Univ. Grenoble Alpes, GIPSA-LAB (CNRS UMR 5216), Dept. Parole & Cognition, Grenoble, France
[d] Univ. de Poitiers, CeRCA (CNRS UMR 7295), F-8600 Poitiers, France

ARTICLE INFO

Article history:
Received 7 January 2014
Revised 14 November 2014
Accepted 17 November 2014

Keywords:
Handwriting
Spelling
Motor production
Children
Cascade

ABSTRACT

How do we recall a word's spelling? How do we produce the movements to form the letters of a word? Writing involves several processing levels. Surprisingly, researchers have focused either on spelling or motor production. However, these processes interact and cannot be studied separately. Spelling processes cascade into movement production. For example, in French, producing letters PAR in the orthographically irregular word PARFUM (perfume) delays motor production with respect to the same letters in the regular word PARDON (pardon). Orthographic regularity refers to the possibility of spelling a word correctly by applying the most frequent sound-letter conversion rules. The present study examined how the interaction between spelling and motor processing builds up during writing acquisition. French 8–10 year old children participated in the experiment. This is the age handwriting skills start to become automatic. The children wrote regular and irregular words that could be frequent or infrequent. They wrote on a digitizer so we could collect data on latency, movement duration and fluency. The results revealed that the interaction between spelling and motor processing was present already at age 8. It became more adult-like at ages 9 and 10. Before starting to write, processing irregular words took longer than regular words. This processing load spread into movement production. It increased writing duration and rendered the movements more dysfluent. Word frequency affected latencies and cascaded into production. It modulated writing duration but not movement fluency. Writing infrequent words took longer than frequent words. The data suggests that orthographic regularity has a stronger impact on writing than word frequency. They do not cascade in the same extent.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Writing is one of the most important communicational tools in humans. With the arrival of the internet, tablets and smartphones many people spend more time writing emails, chatting or communicating via Short Message System (SMS) than speaking. Despite the importance of writing in our society, the studies investigating written language production are very scarce. How do we recall a word's spelling when we need to write it? How do we produce the movements to form its letters? The answers to these questions are extremely limited. We know even less about how children learn to write. This study examined writing processes from a developmental perspective. We investigated how and when spelling and motor processes interact during writing acquisition.

* Corresponding author at: Université Grenoble 2, Laboratoire de Psychologie et NeuroCognition (CNRS UMR 5105), BSHM – BP 47, 38040 Grenoble Cedex 09, France. Tel.: +33 476 82 56 30.

E-mail address: Sonia.Kandel@upmf-grenoble.fr (S. Kandel).

http://dx.doi.org/10.1016/j.cognition.2014.11.014
0010-0277/© 2014 Elsevier B.V. All rights reserved.

1.1. Central and peripheral processing in written language production

Writing is a linguistic motor task that involves different processing stages. Surprisingly, researchers have either focused on spelling or motor production. The relationship between the two has hardly received any attention. Spelling refers to central processing. Movement production is instead related to peripheral processing. The distinction between central and peripheral processing levels comes from neuropsychological studies (e.g., Baxter & Warrington, 1986). Patients presenting central dysgraphia had difficulties with spelling processes. Case studies presenting peripheral dysgraphia exhibited difficulties with the motor aspects of writing. The clinical independence of these deficits led researchers to dissociate them. With the introduction of neuroimaging techniques the distinction was confirmed at the neural level (e.g., Beeson et al., 2003). Two recent meta-analyses reflect this view by examining the neural substrates of central and peripheral processing separately (Planton, Jucla, Roux, & Démonet, 2013; Purcell, Turkeltaub, Eden, & Rapp, 2011).

Central processes refer to spelling because word writing involves the selection and activation of orthographic representations (orthographic lexemes). This allows for the recall of the words' letter components and their organization (Caramazza & Miceli, 1990). Most researchers thought that spelling processes are complete before movement initiation. For this reason, they essentially presented latency data. Latency refers to the temporal lapse between word presentation and motor execution. It is informative about the processes involved in lexical access. Researchers investigated for example how letter-sound relationships affected spelling recall (Afonso & Álvarez, 2011; Bonin, Peereman, & Fayol, 2001; Qu, Damian, Zhang, & Zhu, 2011; Zhang & Damian, 2010). This approach elaborated *central* writing models. They included a low level processing "device" devoted to movement production. However, none of the models provided clear information on how writing movements were programmed and produced (e.g., Bonin et al., 2001; Caramazza, 1997). In addition, they did not consider any kind of interaction between the central and peripheral aspects of the writing process. Neuropsychological studies proposed similar models (e.g., Rapp, Epstein, & Tainturier, 2002). The data referred to writing errors produced by dysgraphic patients with impaired orthographic processing (Beaton, Guest, & Ved, 1997; Miceli, Benvegnú, Capasso, & Caramazza, 1997; Rapp, Benzing, & Caramazza, 1997).

On the other hand, research on handwriting production referred to *peripheral* processing. They investigated the selection and activation of motor programs (van Galen, Smyth, Meulenbroek, & Hylkema, 1989). Motor programs contain information on letter shape, stroke order and direction (Teulings, Thomassen, & Van Galen, 1983). These studies reported data on letter and symbol production, but not words. Latency was an indicator of motor program recall and movement preparation. Other measures like movement time and writing speed provided information on motor production *per se*. The idea was to gain understanding on movement control. They did not consider that writing has a communication function. They neglected the implication of higher order linguistic information such as word spelling. In this perspective, we produce one letter after another by activating its corresponding motor program. The movements to produce a letter should be identical, regardless of its spelling specifications.

In sum, most writing research ignored the relationship between central and peripheral processing. van Galen (1991) presented a handwriting model that integrated the two components of writing. He proposed higher order linguistic modules that initiate the writing process: activation of intentions, semantic retrieval and syntactical construction. They were taken from Levelt's (1989) model of speech production because these processes are common to all linguistic movements. He referred to previous speech research for descriptions on how each module functions. These three modules provide input into a spelling module. The information on how lexical selection and activation operated is rather limited. In contrast, he presented abundant details on the processing levels that follow spelling: selection of allographs, size control and muscular adjustment. The low level motor processes regulate the local aspects of letter production. van Galen's (1991) model postulated parallel processing from higher to lower level modules. The central high level modules are always active before peripheral low levels. This occurs because the higher level modules anticipate information on the following parts of the word. This points to the idea of an interaction between central and peripheral processing. Nevertheless, van Galen's model did not describe how the spelling and motor components of writing communicate.

Van Galen referred to dual-route conceptions of spelling. He did not adopt them because he argued that the independence of the two routes was under debate (e.g., Humphreys & Evett, 1985). He concluded the description of the spelling module by stating that "for reasons of simplicity" he preferred an "undifferentiated spelling module" (van Galen, 1991; p. 184). So, according to van Galen's (1991) model, to write a word we will activate its orthographic representation at the spelling module. The representation consists of a linear sequence of letters. It codes letter identity and order (e.g., $C_1A_2M_3E_4R_5A_6$; see Kandel, Peereman, Grosjacques, & Fayol, 2011 for a discussion on orthographic encoding). It is stored in the orthographic buffer until it can be "unwrapped" for serial production. It constitutes the input to the peripheral modules (i.e., allographs, size control and muscular adjustment).

1.2. The interaction between central and peripheral processing

Do central processes affect peripheral ones? Recent research on adult handwriting production suggests that spelling processes modulate the timing of motor processes. Delattre, Bonin, and Barry (2006) manipulated word frequency and orthographic regularity. Word frequency refers to the number of occurrences of a word. Orthographic regularity concerns the possibility of spelling a word correctly by applying the most frequent phoneme–grapheme conversion rules. For example, the French word PARDON (pardon, /paRdɔ~/) is an orthographically regular word. It is regular because the most frequent phoneme–grapheme mappings lead to the correct spelling: P = /p/, A = /a/, R = /R/, D = /d/, ON = /õ/. In contrast, PARFUM (perfume, /paRfε~/) is orthographically irregular. The application of sound-letter transcription rules leads to incorrect spellings like *PARFAIN or *PARFIN. A *UM* ending is rather an exception. The words were dictated, and the participants wrote them on a digitizer. Latencies were longer for irregular than regular words but only when they were infrequent. This indicates that spelling processes were modulated by orthographic regularity and word frequency. They were active before the participants started to write. Writing duration was an indicator of motor processing during movement production. It referred to the time the pen was on the digitizer from the beginning to the end of the word. The durations were longer for irregular than regular words. These differences concerned low-frequency words. It is noteworthy that the analyses were only significant in the by-participants analysis.[1] The word frequency factor did not reach significance. The authors claimed that the spelling processes involved in solving the orthographic irregularity conflict were not finished before movement initiation (Rapp et al., 2002). Damian and Stadthagen-Gonzalez (2009) found the opposite pattern of results. They manipulated phonological similarity to examine the influence of phonology on writing movements. They observed that spelling processes did not affect writing duration. They concluded that the participants completed lexical access and then initiated the motor response.

However, other data from typing research support the idea that spelling processes modulate written production. In Dutch, orthographic irregularity slowed down performance when typing words. There was an increase in preparation and typing time for irregular words with respect to regular ones (Bloemsaat, van Galen, & Meulenbroek, 2003). Furthermore, Lambert, Alamargot, Larocque, and Caporossi (2011) provided further evidence for the interaction between spelling and motor production with eye and pen movement measures. They extended the findings beyond the production of isolated words. The participants had to copy a series of words. This is a more "ecological" task than writing isolated words. They manipulated orthographic regularity and word frequency. They observed that spelling and motor processes are active simultaneously. The participants behaved in an anticipatory fashion. They looked at the model for producing the following word while they were still writing the previous word. The back-and-forth eye and pen movements were modulated by the words' orthographic regularity and frequency. This indicates that central spelling processes were active simultaneously to the peripheral writing mechanisms.

A recent study investigated *how* and *when* spelling and motor processing interact. Roux, McKeeff, Grosjacques, Afonso, and Kandel (2013) examined the extent of the cascade in word writing. The previous studies analyzed the duration of the whole word (Damian & Stadthagen-Gonzalez, 2009; Delattre et al., 2006). Lambert et al. (2011) measured mean letter duration. Their analysis was conducted on the total movement time to write a word divided by the number of letters. Roux et al. (2013) instead, used more a fine-grained methodology. They measured the duration of each letter in the word. With this technique they observed how movement time evolved as the participants wrote one letter after another throughout the word. Their data revealed that letter production does not merely depend on its shape. The way we encode it orthographically also affects the timing of motor production. Letters P, A and R in the irregular word <u>PAR</u>FUM were longer than in the regular word <u>PAR</u>DON. This contrasts with the predictions of the "central" and "peripheral" approaches. They all predict equivalent movement kinematics for producing letters PAR. For the former, the orthographic differences between the two types of words should be solved at a central level (Bonin, Roux, Barry, & Canell, 2012; Damian & Freeman, 2008; Logan & Zbrodoff, 1998). The differences should only be observed before starting to write. The "motor" studies predict the same outcome because writing PAR consists of activating the motor programs for P, A and R. Roux et al.'s analysis also revealed that the impact of orthographic regularity was modulated by the position of the irregularity within the word. When the irregularity was in initial position (e.g. M<u>ON</u>SIEUR, sir), the cascade only affected the timing of the initial letters. When it was located at the end of the word (e.g., PARF<u>UM</u>), the cascade persisted throughout the word until the position of the irregularity was reached. Roux et al.'s (2013) fine-grained methodology thus provides information on the *locus* of the interaction between central and peripheral processing. They also observed at the initial letter positions that movement time was longer for words than pseudo-words. It was longer for pseudo-words at the end of the word. This is evidence that lexical (lexicality) and sublexical (orthographic regularity) central processes produce different types of cascades.

Other spelling characteristics like letter doubling also regulate the dynamics of word production (Kandel, Peereman, & Ghimenton, 2013). In the studies mentioned above, the orthographic regularity effect resulted from conflicting spellings between lexical and sub-lexical levels (Rapp et al., 2002). Letter doubling instead, is specifically coded in the word's orthographic representation. The timing for producing letters DIS in the English word DI<u>SS</u>IPATE was different from DI<u>SG</u>RACE. The latencies, letter duration (i.e., D, I and S) and intervals between letters (i.e., D-I and I-S) were shorter in DI<u>SS</u>IPATE than DI<u>SG</u>RACE. The presence of the doublet facilitated the production of the initial letters until the doublet was completed. Orthographic activation thus spread into the motor processes that regulate movement execution. Again, these differences cannot be accounted for by the "central" or "peripheral" models of writing. The two perspectives would predict equivalent duration for letters DIS. The data support the idea that orthographic processes cascaded onto peripheral processing.

In summary, these studies provide evidence for a functional interaction between spelling and motor processing. Writing research investigating the *format* of orthographic representations supports this view. It revealed that a word's grapheme (Kandel & Spinelli, 2010), syllable

[1] If we calculate the F'min (Clark, 1973, p. 347) the interaction between orthographic regularity and word frequency on total duration is not significant (F'min(1,81.77) = 1.03).

(Kandel, Alvarez, & Vallée, 2006; Kandel et al., 2011) and morpheme structures (Kandel, Spinelli, Tremblay, Guerassimovitch, & Alvarez, 2012) regulate motor production. In French, for example, Kandel and Spinelli (2010) found that movement time for producing the letter A was shorter in the word CLAVIER (keyboard, /klavje/) than PRAIRIE (meadow; /pRɛRi/). In the former A is a simple grapheme because A = /a/. In the latter A is an element of a complex grapheme: AI = /ɛ/. This is further evidence that spelling and motor processes cannot be investigated independently. Up to now, all the studies we mentioned concerned adult writing. How does the spelling/motor interaction build up during writing acquisition?

1.3. Central and peripheral processing when learning how to write

To learn how to write we must acquire detailed orthographic representations (Frith, 1986; Share, 1995). At the same time, we learn to produce the movements that form letters. Before age 8, letter production is relatively slow. The interaction between spelling and motor processes should be quite limited. Most grapho-motor gestures require extreme control and close sensory guidance (Mojet, 1991). Motor control is cognitively very demanding. The child concentrates on producing the correct shapes and connecting the letters between them. With practice there is a progressive learning of sensory-motor maps. These maps – or motor programs (Teulings et al., 1983) – are stored in long-term memory. They consolidate with frequent usage. This facilitates their access and activation. It also limits the use of sensory feedback and increases movement speed. This requires a long process that ends around 10–11 years old. At this period movement production is fast, implicit and automatic (Halsband & Lange, 2006). In noteworthy that during the acquisition of grapho-motor skills the children's kinematics is extremely variable. With neuro-motor maturation, around age 10, the variability decreases (van Galen, 1993). Grapho-motor skills become automatic. The children can therefore use their cognitive resources for the other components of writing, namely spelling, sentence construction and text elaboration (Maggio, Lété, Chenu, Jisa, & Fayol, 2011; Pontart et al., 2013). So between ages 8 and 11 years, the children's handwriting movements should start being automatic and increasingly interact with spelling processes. When do motor and spelling process get to interact in an adult-like fashion?

A few studies investigated how children elaborate orthographic representations for word writing. They revealed that orthographic information starts affecting motor production between ages 8 to 11. In a French study conducted by Kandel and Valdois (2006) children from ages 6 to 11 wrote familiar regular words and pseudo-words on a digitizer. The results globally indicated that the children programmed their writing movements syllable-by-syllable. They grouped the letters into syllable chunks to facilitate spelling memorization. Another experiment revealed that at around 9 years old the children prefer using orthographic rather than phonological information to elaborate these syllable chunks (Kandel, Herault, Grosjacques, Lambert, & Fayol, 2009). For example, the word FORME (shape, /foRm/) is a mono-syllable in spoken language. In written language instead, it is a bi-syllable: FOR.ME (the dot indicates the syllable boundary). The data on movement time and fluency indicated that the children programmed their movements first for writing FOR and then ME. They prepared the movements to produce the first syllable before starting to write. They prepared the second syllable on-line. In other words, FORME was processed as a bi-syllable rather than a mono-syllable. This is evidence that orthographic information can modulate movement production as soon as writing movements become automatic. Finally, another research carried out with 8–10 year old children revealed that orthographic redundancy may affect the children's writing movements. Kandel et al. (2011) studied orthographic redundancy by manipulating bigram frequency. The results indicated that at age 10 the children's writing movements were sensitive to infrequent bigrams. Taken together these developmental studies support the idea that at ages 9–10 word writing starts to be regulated by orthographic knowledge. This research did not investigate the central/peripheral interaction *per se* but the way words were represented for writing.

An experiment conducted by Søvik, Arntzen, Samuelstuen, and Heggberget (1994) shed some light into the interaction between spelling processes and motor production. It revealed that 9 year old children's movement durations were longer for infrequent than frequent words. This occurred only when the words were long. Unfortunately, there was only one age group so we do not have information on how word processing evolves with age. Kandel and Valdois (2005) presented a study conducted with children of ages 6 and 7. They had to write orthographically regular and irregular French words. These words varied in age of acquisition. The results revealed that writing duration was longer for irregular than regular words. These differences only reached significance for words acquired late. The results were quite unclear regarding the interaction between orthographic regularity and age of acquisition. We believe that this is essentially due to the fact that at this age there is a lot of variability in the children's motor abilities. Therefore, it is difficult to understand what occurred with the spelling processes.

To summarize, our knowledge on the interaction between central and peripheral processing during writing acquisition is even more limited for children than adults. The present research investigated this issue with children of ages 8 through 11. Age 9 is critical because it is the period in which grapho-motor skills start being automatic (Halsband & Lange, 2006; Mojet, 1991). Handwriting becomes a communication tool. With automaticity, orthographic knowledge can be processed in parallel to movement production. This will have an impact on the kinematics of the children's writing movements. So the interaction between central and peripheral processes should start around age 8. It should become stronger with age. To assess this interaction we examined how orthographic variables affect movement production. The children wrote orthographically regular and irregular words varying in word frequency. Word frequency refers to lexical processing. Orthographic regularity concerns sub-lexical processing. We measured latency. This informed us about the time the children needed to prepare the movements to start writing a word. The data on movement duration and fluency provided insight on the kinematics of motor production.

2. Method

2.1. Participants

Sixty-four children participated in this experiment. There were 19 children of age 8 (8;8, SD = 3.99) attending 3rd grade, 21 children of age 9 (9;9, SD = 3.38) attending 4th grade and 24 children of age 10 (10;7, SD = 3.79) attending 5th grade. They were all right-handed and native French-speakers. They came from two schools in the Grenoble urban area. They were tested in April. The teachers reported the reading method was mixed. Reading and writing instruction started in 1st grade (i.e., age 6). None of the participants were repeating or skipping a grade. They attended their grade at the regular age. They all had normal or corrected-to-normal vision. The teachers reported the absence of hearing impairments, learning disability, brain disorders or behavioral problems. School attendance was regular. They participated in the experiment under parental written consent.

2.2. Material

There were 31 orthographically irregular words (e.g., FEMME, /fam/; see Appendix A). A word was considered as irregular when it was it is read incorrectly if applying grapho-phonological conversion rules. We selected as many "exception words" as we could. The idea was to render the conflict between orthography and phonology as strong as possible. Since we could not find enough exception words we chose other words that had very low sound-to-spelling consistency (Manulex-Infra, Peerman, Lété, & Sprenger-Charolles, 2007). The Phoneme–Grapheme association for irregular words was 7425.23. We matched them to 31 orthographically regular words (e.g., FORME, /form/) with highly-consistent sound-to-spelling correspondences (Phoneme–Grapheme association = 9240.69). The words were five to eight letters long. Mean word length was around six (see Table 1).

We tried to match them on letter length as much as possible. A few word pairs differed on one letter. There were 28 high frequency words (142.38 per million; Manulex, Lété, Sprenger-Charolles, & Colé, 2004) and 34 low frequency words (15.06 per million) of equivalent length. The corpus was also controlled for uniqueness point, numbers of letters and phonemes, grapheme, bigram and trigram frequencies (Table 1; LEXIQUE 2, New, Pallier, Brysbaert, & Ferrand, 2004). Since we had to compare letter duration between the regular and irregular words we tried to select words that shared at least the initial letter and up to the first three letters (e.g., PARFUM/PARDON).

2.3. Procedure

Stimulus presentation and movement analysis were controlled by *Ductus* (Guinet & Kandel, 2010). The target word was presented on the center of the screen of a laptop (written in low case Times New Roman size 18). An auditory signal and a fixation point (100 ms duration) preceded word presentation. The child's task was to copy the item on a digitiser (Wacom Intuos 2, sampling frequency 200 Hz, accuracy 0.02 mm). The stimulus remained on the screen until the child finished writing the word. The digitiser was connected to a laptop that monitored the writing movement. The children were instructed to copy the items as they did in class, i.e., in cursive handwriting. They had to write with a special pen (Intuos Inking Pen) on a lined paper that was stuck to the digitiser. The paper was taken from the notebooks the children use to write when they are in school (vertical limit = 0.8 cm, horizontal limit = 17 cm). The children became familiar with the material by writing their name. There were two practice items. We told the children to start writing the word as soon as they could. There were no time limits or speed constraints during writing. The experimenter clicked on a button to start the following trial. The words were randomised across participants. The experiment lasted between 20 to 30 min. The children were tested individually in a quiet room inside the school.

2.4. Data analysis

We analyzed three measures. *Latency* referred to the time between word presentation and the moment the child started to write (pen pressure >0). Letter *duration* concerned the time the children took to write each letter in a word. Movement *fluency* concerned the movements' number of absolute velocity peaks produced when writing each letter (Meulenbroek & van Galen, 1989a, 1989b). To segment the words into letters, we used geometric (cuspids and curvature maxima in the trajectory) and kinematic (tangential velocity minima) criteria (see Fig. 1).

We needed to compare duration and dysfluency values of letters that are made up of different stroke numbers. In Fig. 1 we can see that L has two strokes: an up-stroke and down-stroke. Letter B has more strokes. Therefore, movement duration should be longer for B than L because the former has more strokes than the latter. This would bias the results. Our goal was to examine how spelling – i.e., the linguistic component – affected movement production. So to compare duration and fluency of letters that have different number of strokes, we divided the values by the number of strokes in each letter. We referred to the number of strokes presented in the segmentation of cursive letters by Meulenbroek and van Galen (1990). If for example the duration of the L was 200 ms, then the mean stroke duration was 200/2 = 100 ms. We could thus compare all the letters, irrespective of the number of the strokes they are made up of and at all positions. Duration and dysfluency increases at a given letter position reveal important

Table 1
Linguistic variables for which the words were controlled for. The *p*-values refer to the comparison between Irregular and Regular words (*p*-values Regularity) and High and Low Frequency words (*p*-values Frequency).

	Irregular words	Regular words	*p*-values Regularity	High frequency words	Low frequency words	*p*-values Frequency
P–G association	7425.23	9240.69	.024	8541.04	8161.6	n.s.
Number of letters	6.03	5.97	n.s.	5.89	6.09	n.s.
Number of phonemes	4.45	4.42	n.s.	4.32	4.53	n.s.
Uniqueness Point	5.55	5.45	n.s.	5.61	5.41	n.s.
Grapheme frequency	37515.78	38912.63	n.s.	42287.84	34867.66	.004
Bigram frequency	3803.62	4264.42	n.s.	4831.19	3377.53	.024
Trigram frequency	710.23	782.17	n.s.	1023.44	517.88	.015
Lexical frequency	57.55	87.57	n.s.	142.38	15.06	.002

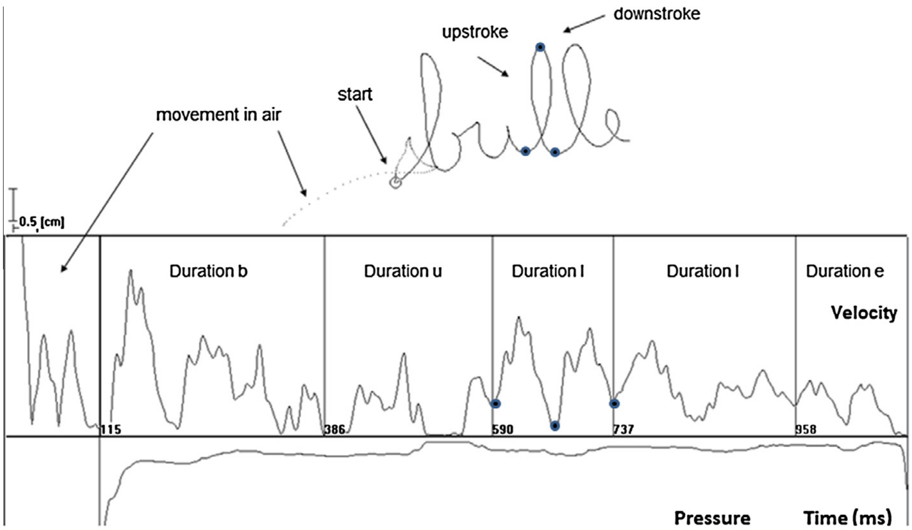

Fig. 1. Example of the analysis of the word BULLE (bubble, /byl/) produced by a 9 year old child. The upper part presents the production of the word. The dotted line shows the trajectory of the movement done in air before starting to write. The lower part shows the velocity and pressure as a function of time (ms). The numbers indicate the *xy* coordinate number. The velocity profile shows how the word was segmented into letters and how durations were computed. The dots show how letter L was segmented into upstroke and downstroke.

processing loads (Meulenbroek & van Galen, 1989a, 1989b; van Galen, Meulenbroek, & Hylkema, 1986). Since the shorter words in the corpus were five letters long, we analyzed the duration and fluency measures of the first five letters. The reason for doing this is a loss of statistical power in the analyses from letter positions 6 through 8. For example, there are 18 words that did not have duration and dysfluency values for letter 6. Since there are 66 participants, the analysis would only compute 1188 values out of 4092. This constitutes a 30% data loss that would unbalance the power of the analyses for letter position. We did not analyze errors because they were extremely rare. The words that were misspelled were not analyzed. It is also noteworthy that we took take gaze lift measures during the copying task with *Ductus*' event marking device. We could not analyze them because they were very few (see Kandel & Valdois, 2006). The data sample was so limited that we could not apply any analysis on it.

The statistical analyses were performed on latencies, stroke duration and fluency values. The studentized residuals that were larger than twice the standard deviations were considered outliers and removed (Baayen, 2008). We used the R-software (R version 3.0.; package lme4, Bates, Maechler, Bolker, & Walker, 2014) to run ANOVAs with mixed-effect analyses (Baayen, 2008; Pinheiro & Bates, 2000). Items and participants were random-effect variables. Orthographic regularity (regular words *vs.* irregular words), word frequency (high frequency words *vs.* low frequency words), letter position (L1, L2, L3, L4, L5) and age (8, 9, 10) were fixed-effects variables. We included in all the analyses the most complex adequate adjustment model (i.e., adjustment on intercept and slopes; Bar, Levy, Scheepers, & Tily, 2013). All the mixed-effects were tested using likelihood ratio tests (Pinheiro & Bates, 2000). For all the tests, the *p-values* refer to the *F* values on the Fisher distribution. The error degree of freedom was computed by the substraction of the number of observations and the

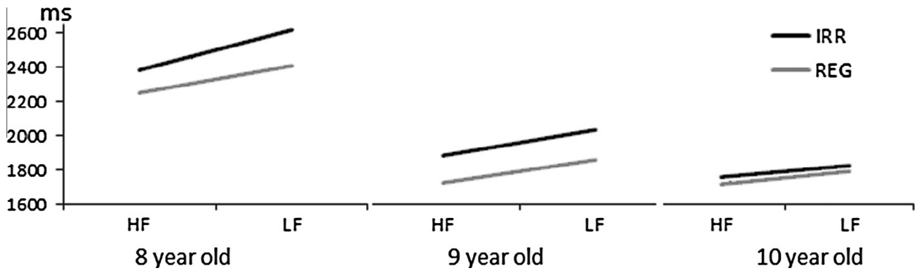

Fig. 2. Mean latency (in milliseconds) for high (HF) and low-frequency (LF) regular (REG) and irregular (IRR) words for the three groups.

number of conditions (N−n−1). Finally, we used orthogonal contrasts for multiples comparisons. We only reported the results that reached statistical significance.

3. Results

3.1. Latencies

Thirty-two errors (0.81%) and 132 outlier values (3.32%) were excluded from the analyses. None of the mixed-effects reached significance ($\chi^2s < 1$). Fig. 2 presents the latency values for high and low frequency irregular and regular words for each age group. Irregular words yielded longer latencies than regular ones, $F(1,3803) = 5.56$, $p = .0184$. Latencies were shorter for high frequency words than low frequency words, $F(1,3803) = 7.67$, $p = .0056$. Age yielded significant effects, $F(2,3803) = 13.62$, $p < .0001$. Planned comparisons revealed that the 8 year olds took longer to start writing words than the children of age 9, $t(3803) = -3.60$, $p = .0002$. The latter were in turn slower than the children of age 10, $t(3803) = -1.90$, $p = .0288$.

The interaction between age and orthographic regularity was significant, $F(2,3803) = 7.41$, $p = .0006$. The simple effect analyses indicated that orthographic regularity modulated latencies for the 8 and 9 year olds, $t(1131) = -2.47$, $p < .01$ and $t(1238) = -2.73$ $p = .0032$, respectively. Orthographic regularity did not yield significant differences for the 10 year old children.

3.2. Movement duration

One error (0.005%) and 758 outlier values (3.81%) were excluded from the analyses. None of the mixed-effects reached significance ($\chi^2s < 1$). Durations were longer for irregular than regular words, $F(1,19{,}083) = 9.91$, $p < .0001$. Fig. 3 presents stroke duration values for irregular and regular words at each letter position for each age group. Movement duration also decreased with age, $F(2,19{,}083) = 29.63$, $p < .0001$. The 8 year olds took longer to write the words than the 9 year olds, ($t(19{,}083) = -4.55$, $p < .0001$. Durations for 9 and 10 year olds were equivalent ($t < 1$). The main effect of letter position indicated that durations were longer at the beginning of words than at the end, $F(4,19{,}083) = 115.49$, $p < .0001$.

Orthographic regularity interacted with letter position, $F(4,19{,}083) = 21.11$, $p < .0001$. Moreover, there was a second order interaction indicating that age modulated the interaction between orthographic regularity and letter position, $F(8,19{,}083) = 2.58$, $p = .0082$. The first order interaction was significant for the three groups: 8 year olds, $F(4,5630) = 8.34$, $p < .0001$; 9 year olds, $F(4,6262) = 6.09$, $p < .0001$; 10 year olds, $F(4,7190) = 6.49$, $p < .0001$. As Fig. 3 shows, at L2 the regularity effect was significant for the 9 ($t(1252) = -2.31$, $p = .0105$) and 10 year old children ($t(1438) = -2.05$, $p = .0203$). At L4, it was significant for 8 year olds ($t(1126) = -2.81$, $p = .0025$), 9 year olds ($t(1252) = -2.31$, $p = .0105$) and 10 year olds ($t(1438) = -2.12$, $p = .0171$).

Age interacted with orthographic regularity, $F(2,19{,}083) = 7.70$, $p = .0005$. The simple effects analyses revealed that the stroke duration differences between regular and irregular words decreased with age: 8 year olds, $t(5630) = -2.68$, $p = .0037$; 9 year olds, $t(6262) = -3.16$, $p = .00018$; 10 year olds, $t(7190) = -2.82$, $p = .0024$. Also, age interacted with letter position ($F(8,19{,}083) = 7.79$, $p < .0001$). Movement duration for 8 year olds fluctuated

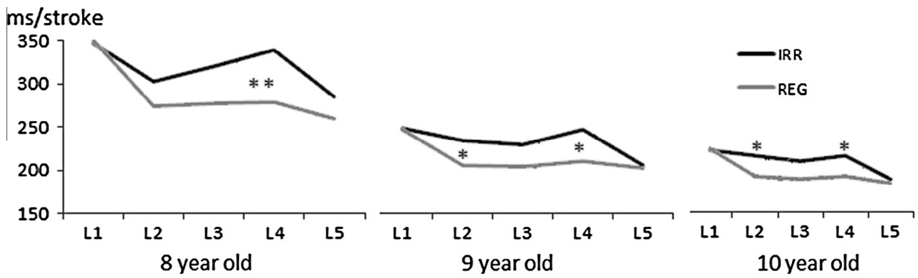

Fig. 3. Movement duration (ms/stroke) at each letter position (letter 1 (L1), letter 2 (L2), letter 3 (L3), letter 4 (L4), letter 5 (L5)) for regular (REG) and irregular words (IRR) as a function of age. $^{*}p < .05$; $^{**}p < .001$.

at the beginning (L1) and end (L4) of the words. This fluctuation was less pronounced for the older children.

Fig. 4 presents stroke duration values for high- and low-frequency words at each letter position for each age group.

Durations were also longer for low frequency than for high frequency words, $F(1,19{,}083) = 4.43$, $p = .0353$. Moreover, word frequency effects were modulated by letter position, $F(4,19{,}083) = 10.55$, $p < .0001$. Durations were longer for low frequency words than high frequency words at L3, $t(3816) = 1.99$, $p = .0233$.

3.3. Movement fluency

825 outlier values (4.15%) were excluded from the analyses. None of the mixed-effects reached significance ($\chi^2s < 1$). Fig. 5 presents the movement fluency values for irregular and regular words at each letter position for each age group. Writing movements were more fluent for regular than irregular words, $F(1,19{,}015) = 5.58$, $p = .0182$. Word frequency did not have an impact on fluency, $F(1,19{,}015) = 2.61$, $p = .1062$. Movement fluency evolved with age, $F(2,19{,}015) = 27.59$, $p < .0001$. The 8 year old children's movements were less fluent than the 9 year olds, $t(5600) = -3.81$, $p < .0001$. Letter position was significant, $F(4,19{,}015) = 10.09$, $p < .0001$.

The interaction between orthographic regularity and age was significant, $F(2,19{,}015) = 3.47$, $p = .0311$. Orthographic regularity modulated the number of velocity peaks per stroke at all ages: 8 year olds, $t(5600) = -2.34$, $p = .0097$; 9 year olds, $t(6234) = -2.12$, $p = .0170$ and 10 year olds, $t(7180) = -2.58$, $p < .0049$. Also, age interacted with letter position, ($F(8,19{,}015) = 4.08$, $p < .0001$).

Letter position interacted with orthographic regularity, $F(4,19{,}015) = 15.41$, $p < .0001$. This first order interaction was modulated by age, $F(8,19{,}015) = 3.67$, $p = .0003$. The interaction between orthographic regularity and letter position were significant at all ages: age 8, $F(4,5600) = 5.77$, $p = .0001$; age 9, $F(4,6234) = 6.36$, $p < .0001$; and age 10, $F(4,7180) = 4.71$, $p = .00019$. As Fig. 5 shows, at L2 the children's movements were more dysfluent for irregular than regular words at ages 9 and 10, $t(6234) = -2.24$, $p = .0126$ and $t(7180) = -2.07$, $p = .0192$, respectively. The age 8 children were more dysfluent for irregular than regular words at L4, $t(5600) = -2.31$, $p = .0104$.

4. Discussion

This study examined how spelling and motor processes interact during the acquisition of writing skills. We focused on how the interaction builds up when writing movements start to become automatic. Spelling processes concern the activation of information on a word's letter constituents. They are also constrained by the linguistic organization of the words we want to write. They are active *before* we start writing the words. When spelling and motor processes interact, the activation spreads or cascades *while* we write the words. This developmental investigation tapped into spelling sub-lexical (orthographic regularity) and lexical (word frequency) activation. We measured

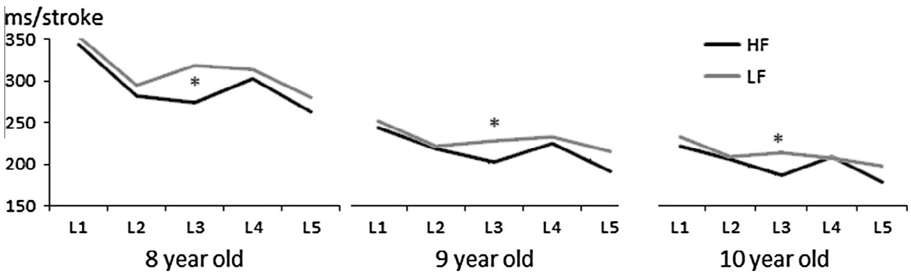

Fig. 4. Movement duration (ms/stroke) at each letter position (letter 1 (L1), letter 2 (L2), letter 3 (L3), letter 4 (L4), letter 5 (L5)) for high-frequency (HF) and low-frequency (LF) words as a function of age. *$p < .05$.

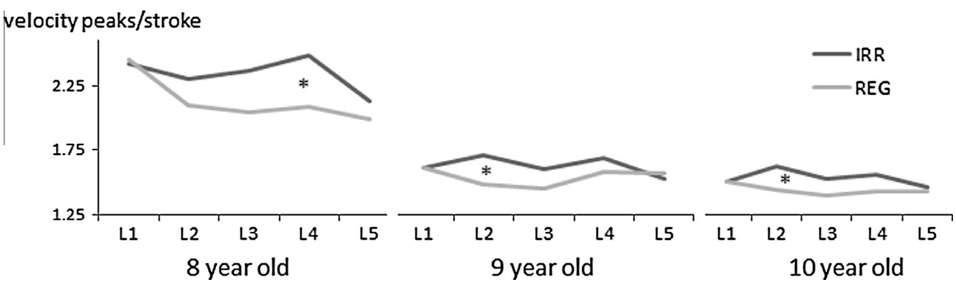

Fig. 5. Movement fluency (velocity peaks/stroke) at each letter position (letter 1 (L1), letter 2 (L2), letter 3 (L3), letter 4 (L4), letter 5 (L5)) for regular (REG) and irregular (IRR) words as a function of age. *$p < .05$.

latency as an indicator of the processes that occur before the writing movement begins. To examine how these spelling processes interacted with motor processing we measured movement duration (stroke duration) and fluency (number of velocity peaks per stroke). These measures were computed letter-by-letter so we could observe how the cascade evolved from the beginning to the end of the word. The results revealed that lexical and sub-lexical activation affected motor production. This is evidence for an interaction between spelling and motor processes already at age 8. The way these processes interacted varied with age. The modulation of the interaction seems to be linked to the proficiency of writing skills.

The data indicated that latency, duration and dysfluency values were systematically higher for 8 year olds than the older children. For 9 and 10 year olds the three measures were globally equivalent. Previous developmental studies also reported that movement duration and dysfluency decreases between ages 8 and 9 (Meulenbroek & van Galen, 1989a, 1989b, 1990; Mojet, 1991; Zesiger, Mounoud, & Hauert, 1993). They become relatively stable around age 10. The decrease is mainly due to motor maturation and practice. Sensory-motor maps are stable and can be accessed easily. Writing movements are fast and smooth. They require less sensory control. This results in a decrease in cognitive load. The consequence is that writing movements become automatic, more stable and adult like. The data of the present study suggest that the children's writing movements became stable and automatized between ages 9 and 10. Letter position also affected movement duration and fluency. The initial letters took longer to write and were produced with less fluency than the letters located towards the end of the words. That the duration decreases progressively towards the end of the words, is in agreement with the previous word writing experiments (e.g., Kandel et al., 2013; Roux et al., 2013). This is likely due to a gradual decrease of the cognitive resources that are required to keep the orthographic representation active while producing other letters. Nevertheless, the fluctuation was more important for the 8 year olds than the older children. The younger children also had to deal with the cognitive load imposed by grapho-motor control because their writing was still not completely automatic.

How does the interaction between spelling and motor processes build up during the stabilization of writing skills? The data globally revealed that orthographically irregular words required more processing demands than regular words. This "regularity effect" has been documented in previous research in adults (Delattre et al., 2006; Roux et al., 2013). It can be accounted for by the dual-route framework presented by Rapp et al. (2002). Lexical and sublexical routes operate in parallel. On one hand, there is an activation of the orthographic representation at a semantic-lexical level. The irregular word PARFUM for example should activate the representation of *PARFUM* that is stored in the orthographic lexicon. The output will be PARFUM. On the other hand, at a sublexical level, a transcription mechanism produces an output that is regulated by sound-letter correspondence frequency. PARFUM should yield "PARFIN", which is not the correct spelling, but IN is the most frequent spelling for the final phoneme. Since the outputs of the two operations do not match (PARFUM and PARFIN) there is a conflict. Its resolution requires more processing time than when there is no mismatch.

The way orthographic regularity affected the children's productions varied with age. The latency data revealed that orthographic regularity affected the 8 and 9 year old children. Latencies for 10 year olds were equivalent for irregular and regular words. This suggests that 10 year olds do not start solving the conflict generated by irregular words before starting to write. This is in line with what was previously observed with adults (Roux et al., 2013). For movement duration and fluency measures, orthographic irregularity had an impact at all ages. It was larger for the younger children. Furthermore, for 8 year olds orthographic regularity mostly affected the production of the letters at the end of the words. For the 9 and 10 year olds the regularity effect was present at the initial and final portions of the words. The persistence of orthographic processing during movement production is in line with adult data presented by Delattre et al. (2006) in spelling-to-dictation and Roux et al. (2013) in word copying. Solving this conflict has consequences beyond movement preparation. It spreads and delays movement production. Roux et al.'s (2013) study showed that when the orthographic irregularity is at the end of the word the conflict increases movement time until it is solved. The present research confirms these findings with children and provides evidence for an interaction between spelling and motor processing during writing acquisition.

The spelling-motor interaction was present already at age 8. It became more adult-like at ages 9 and 10. At age 8, the regularity effect was important for latencies. It did not affect the kinematics of the movements that produced the initial letters. It was only observed at the end of the words. This pattern of results suggests that the 8 year olds solved most of the orthographic conflict before starting to write. This would avoid a cognitive overload due to the simultaneous processing of the spelling and grapho-motor execution. The impact on movement duration and fluency at the beginning of the word was therefore limited. For the 9 and 10 year olds, irregular words yielded longer durations than regular words at the beginning and end. This is in line with adult data (Roux et al., 2013). With the automation of writing skills the motor processing load decreases. The children can start writing the word before the orthographic conflict is solved.

In summary, the present study provides evidence on how the interaction between spelling and motor processing appears during writing acquisition. When grapho-motor skills start being automatic (age 8) sublexical processing affects movement preparation as well as the motor processes that produce the final letters. Then at age 9, sublexical processing also modulates the movements that produce the initial letters of the words. At age 10, orthographic irregularity no longer affects the processes taking place before starting to write. It regulates letter production throughout the whole word. The children produce the words very much like adults (Roux et al., 2013).

Word frequency also had an impact on the timing of the children's productions. Low frequency words produced longer latencies than high frequency words. This suggests that the activation of low frequency words took longer than high frequency words. Our digitizer data revealed that these activation differences spread into writing duration. Letter production was numerically longer for low than high frequency words from letter positions 1 to 5. However, the differences were statistically significant only at the middle of the words (at L3). It is noteworthy that word frequency did not affect movement fluency. Orthographic regularity did not interact with word frequency. Taken together, word frequency affected movement preparation and cascaded into movement production by delaying movement time. However, the strength of the cascade is likely to be limited. The interaction between frequency and age did not reach significance. So the impact of word frequency on letter production was apparently similar at all ages. The latency results are partly consistent with adult data presented by Delattre et al. (2006). They observed frequency effects only for irregular words. Word frequency did not affect adult movement time. The main effect of word frequency for writing duration was not reliable. Also, Delattre et al. (2006) reported that word frequency and regularity interacted in the by-participants analysis but not in the by-items analysis (see also footnote 1). This suggests that the impact of word frequency on movement production is not very strong in adults. Therefore, the interaction between word frequency processing and motor processing is stronger in children than in adults. Learning how to write would consist of a progressive decrease of word frequency effects on letter production. The automation of writing skills would reduce the effect of word frequency. Further research needs to be done with younger children to see how spelling and grapho-motor processes evolve before handwriting becomes automatic.

It should be pointed out that our experiment consisted of a copying task. Copying necessarily involves an initial process that leads to the visual identification of the letter string. One could argue that the orthographic regularity and word frequency effects we observed could be accounted for in terms of input processing. Research on reading processes have widely documented regularity and word frequency effects (see for example Sprenger-Charolles, 2003 for a developmental study in French). A series of studies do not support this view. Álvarez, Cottrell, and Afonso (2009) presented digitizer data on handwriting indicating that spelling to dictation and picture naming tasks yielded equivalent effects than copying words from the screen. It is therefore unlikely that word recognition processes affected the kinematics of writing. Furthermore, recent developmental research examined the common visual components of copying and reading tasks (Bosse, Kandel, Prado, & Valdois, 2014). French children of ages 8–10 read and copied the same text. The authors measured eye movements during reading and gaze lifts during copying. The data revealed that the processes that are common to both tasks are related to early extraction of letter information. In particular, the relationship between rightward fixations and gaze lifts was linked to the number of letters analyzed simultaneously. High order linguistic variables such as word frequency are more likely to affect fixation duration and regression rate (Hyönä & Olson, 1995). It is also noteworthy that orthographically irregular words should produce a stronger conflict in spelling than reading processes. Phoneme–grapheme consistency in French is much lower than grapheme–phoneme correspondences (Peereman & Content, 1999; Ziegler, Jacobs, & Stone, 1996). If reading processes affected the way the children copied the words, latencies should have been systematically longer for irregular than regular words. We did not observe this pattern of results for the 10 year olds. Roux et al. (2013) did not observe an orthographic regularity effect on adult latencies either. Finally, previous research on word and pseudo-word copying provided data indicating that French 1st and 2nd graders lifted their gaze to look at the target while copying (Kandel & Valdois, 2006). The children from 3rd to 5th grade – i.e., from ages 8 to 10 – hardly ever lifted their gaze to look at the model. Starting at age 8, the children could memorize the spelling of the word and pseudo-word in a single fixation. They could write it without taking another glance at the target. We confirmed this in our experiment. Once the children started to write the target word they did not do any more visual processing on the target. Therefore, it is unlikely that there is parallel visual processing of the model and movement production in our writing task.

To conclude, the data revealed that orthographic regularity has a much stronger impact on the children's writing than word frequency. The interaction between central and peripheral processes cascaded differently for the lexical and sub-lexical levels. Orthographic irregularity produced a conflict at a sub-lexical level that generated a more important cognitive load than word frequency at the lexical level. This observation is in line with the adult data (Delattre et al., 2006). It is noteworthy that reading research, as well as Delattre et al. (2006) for adult handwriting, showed that orthographic regularity generally affected more the timing of low frequency words than high frequency words. We did not observe this pattern of results for latencies, duration or dysfluency. It is therefore likely that the processing of the conflict arising from orthographic irregularity affects the writing of all words, irrespective of their frequency.

Acknowledgments

We would like to thank Géraldine Grosjacques, Hélène Queste and Mélanie Julian for their contribution in the experimental and data processing part of this study. We would also like to thank Helen T. Ramey, MD for helpful comments on previous versions of this manuscript. Special thanks to the school teachers. We acknowledge the financial support from the Institut Universitaire de France and the Agence Nationale de la Recherche (ANR 14-C30-0013-01).

Appendix A. Words used in the experiment. The English translation is in parenthesis.

Irregular words		Regular words	
High frequency words	Low frequency words	High frequency words	Low frequency words
alcool (alcohol)	accroc (snag)	auteur (author)	agneau (lamb)
aspect (aspect)	album (album)	autrui (others)	aigle (eagle)
compte (account)	aplomb (balance)	chacun (each)	aiglon (eaglet)
femme (woman)	asthme (asthma)	forme (shape)	arceau (hoop)
fusil (rifle)	camping (camping)	futur (future)	candeur (naivety)
gentil (nice)	canyon (canyon)	goutte (drop)	castor (beaver)
instinct (instinct)	chorale (chorus)	index (index)	chameau (camel)
monsieur (sir)	compteur (counter)	matin (morning)	chaudron (cauldron)
moyen (means)	dolmen (dolmen)	meilleur (best)	dicton (saying)
parfum (perfume)	escroc (swindler)	pardon (forgive)	endive (chicory)
respect (respect)	faisan (pheasant)	recours (recourse)	flocon (flake)
second (second)	foetus (fetus)	sortir (exit)	fourmi (ant)
tabac (tobacco)	gadget (gadget)	tissu (tissue)	gadoue (mud)
wagon (wagon)	galop (gallop)	vigne (vine)	gazon (grass)
	millier (thousand)		moisson (harvest)
	oignon (onion)		orteil (toe)
	sirop (syrup)		satin (satin)

References

Afonso, O., & Álvarez, C. J. (2011). Phonological effects in handwriting production: Evidence from the implicit priming paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*(6), 1474–1483.

Álvarez, C. J., Cottrell, D., & Afonso, O. (2009). Writing dictated words and picture names: Syllabic boundaries affect execution in Spanish. *Applied Psycholinguistics, 30*, 205–223.

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge, UK: Cambridge University Press.

Bar, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*, 255–278.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1–7, <http://CRAN.R-project.org/package=lme4>.

Baxter, D. M., & Warrington, E. K. (1986). Ideational agraphia: A single case study. *Journal of Neurology, Neurosurgery and Psychiatry, 49*, 369–374.

Beaton, A., Guest, J., & Ved, R. (1997). Semantic errors of naming, reading, writing, and drawing following left-hemisphere infarction. *Cognitive Neuropsychology, 14*, 459–478.

Beeson, P. M., Rapcsak, S. Z., Plante, E., Chargualaf, J., Chung, A., Johnson, S. C., et al. (2003). The neural substrates of writing: A functional magnetic resonance imaging study. *Aphasiology, 17*, 647–665.

Bloemsaat, G., van Galen, G. P., & Meulenbroek, R. G. (2003). Lateralized effects of orthographical irregularity and auditory memory load on the kinematics of transcription typewriting. *Psychological Research, 67*(2), 123–133.

Bonin, P., Peereman, R., & Fayol, M. (2001). Do phonological codes constrain the selection of orthographic codes in written picture naming. *Journal of Memory and Language, 45*, 688–720.

Bonin, P., Roux, J.-S., Barry, C., & Canell, L. (2012). Evidence for a limited-cascading account of written word naming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*, 1741–1758.

Bosse, M. L., Kandel, S., Prado, C., & Valdois, S. (2014). Does visual attention span relate to eye movements during reading and copying? *International Journal of Behavioral Development, 38*(1), 81–85.

Caramazza, A. (1997). How many levels of processing are there in lexical access? *Cognitive Neuropsychology, 14*, 177–208.

Caramazza, A., & Miceli, G. (1990). The structure of graphemic representations. *Cognition, 37*, 243–297.

Clark, H. H. (1973). The language-as-fixed-effect fallacy: A critique of language statistics in psychological research. *Journal of Verbal Learning and Verbal Behavior, 12*, 335–359.

Damian, M. F., & Freeman, N. H. (2008). Flexibility and inflexibility response components: A Stroop study with typewritten output. *Acta Psychologica, 128*, 91–101.

Damian, M. F., & Stadthagen-Gonzalez, H. (2009). Advance planning of form properties in the written production of single and multiple words. *Language and Cognitive Processes, 24*, 555–579.

Delattre, M., Bonin, P., & Barry, C. (2006). Written spelling to dictation: Do irregularity effects persist on writing durations? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 1330–1340.

Frith, U. (1986). A developmental framework for developmental dyslexia. *Annual of Dyslexia, 36*, 69–81.

Guinet, E., & Kandel, S. (2010). Ductus: A software package for the study of handwriting production. *Behavior Research Methods, 42*, 326–332.

Halsband, U., & Lange, R. K. (2006). Motor learning in man: A review of functional and clinical studies. *Journal of Physiology, 99*, 414–424.

Humphreys, G. W., & Evett, L. J. (1985). Are there independent lexical and nonlexical routes in word processing? An evaluation of the dual route theory of reading. *Behavior Brain Science, 8*, 689–740.

Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: Effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*(6), 1430–1440.

Kandel, S., Alvarez, C., & Vallée, N. (2006). Syllables as processing units in handwriting production. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 18–31.

Kandel, S., Herault, L., Grosjacques, G., Lambert, E., & Fayol, M. (2009). Orthographic vs. phonologic syllables in handwriting production. *Cognition, 110*(3), 440–444.

Kandel, S., Peereman, R., & Ghimenton, A. (2013). Further evidence for the interaction between central and peripheral processes: The impact of double in writing English words. *Frontiers in Psychology, 4*, 729. http://dx.doi.org/10.3389/fpsyg.2011.00729.

Kandel, S., Peereman, R., Grosjacques, G., & Fayol, M. (2011). For a psycholinguistic model of handwriting production: Testing the syllable-bigram controversy. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 1310–1322.

Kandel, S., & Spinelli, E. (2010). Processing complex graphemes in handwriting production. *Memory & Cognition, 38*, 762–770.

Kandel, S., Spinelli, E., Tremblay, A., Guerassimovitch, H., & Alvarez, C. (2012). Processing prefixes and suffixes in handwriting production. *Acta Psychologica, 140*, 187–195.

Kandel, S., & Valdois, S. (2005). The effect of orthographic regularity on children's handwriting production. *Current Psychology Letter: Brain Behaviour and Cognition, 17*, 3.

Kandel, S., & Valdois, S. (2006). Syllables as functional units in a copying task. *Language and Cognitive Processes, 21*, 432–452.

Lambert, E., Alamargot, D., Larocque, D., & Caporossi, G. (2011). Dynamics of the spelling process during a copying task: Effects of regularity and frequency. *Canadian Journal of Experimental Psychology, 65*(3), 141–150.

Lété, B., Sprenger-Charolles, L., & Colé, P. (2004). MANULEX: A grade-level lexical database from French elementary school readers. *Behavior Research Methods, Instruments, & Computers, 36*, 156–166.

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. Cambridge, MA: The MIT Press.

Logan, G. D., & Zbrodoff, N. J. (1998). Stroop-type interference: Congruity effects in colour naming with typewritten responses. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 978–992.

Maggio, S., Lété, B., Chenu, F., Jisa, H., & Fayol, M. (2011). Tracking the mind during writing: Immediacy, delayed, and anticipatory effects on pauses and writing rate. *Reading & Writing: An Interdisciplinary Journal, 25*, 2131–2151.

Meulenbroek, R. G. J., & van Galen, G. P. (1990). Perceptual-motor complexity of printed and cursive letters. *Journal of Experimental Education, 58*, 95–110.

Meulenbroek, R. G. J., & van Galen, G. P. (1989a). The acquisition of skilled handwriting: Discontinuous trends in kinematic variables. In A. M. Colley & J. R. Beech (Eds.), *Cognition and action in skilled behaviour* (pp. 93–101). North Holland: Elsevier Science Publishers BV.

Meulenbroek, R. G. J., & van Galen, G. P. (1989b). The production of connecting strokes in cursive writing: Developing co-articulation in 8 to 12 year-old children. In R. Plamondon, C. Y. Suen, & M. L. Simner (Eds.), *Computer recognition and human production of handwriting* (pp. 105–118). Singapore: World Scientific.

Miceli, G., Benvengnú, B., Capasso, R., & Caramazza, A. (1997). The independence of phonological and orthographic lexical forms: Evidence from aphasia. *Cognitive Neuropsychology, 14*, 35–70.

Mojet, W. (1991). Characteristics of developing handwriting skills in elementary education. In J. Wann, A. Wing, & N. Sovik (Eds.), *Development of graphic skills* (pp. 53–75). London: Academic Press.

New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). LEXIQUE 2: A new French lexical database. *Behavior Research Methods, Instruments, & Computers, 36*, 516–524.

Peereman, R., & Content, A. (1999). LEXOP: A lexical database providing orthography–phonology statistics for French monosyllabic words. *Behavioral Methods, Instruments and Computers, 31*, 376–379.

Peerman, R., Lété, B., & Sprenger-Charolles, L. (2007). Manulex-infra: Distributional characteristics of grapheme–phoneme mappings, and infralexical and lexical units in child-directed written material. *Behavior Research Methods, 39*, 593–603.

Pinheiro, J. C., & Bates, D. M. (2000). *Mixed-effects models in S and S-PLUS*. New York, USA: Springer.

Planton, S., Jucla, M., Roux, F. E., & Démonet, J. F. (2013). The ''handwriting brain''. A meta-analysis of neuroimaging studies of motor versus orthographic processes. *Cortex, 49*(10), 2772–2787.

Pontart, V., Bidet-Ildei, C., Lambert, E., Morisset, P., Flouret, L., & Alamargot, D. (2013). Influence of handwriting skills during spelling in primary and lower secondary grades. *Frontiers in Psychology (Research Topic "Writing words: From brain to hand(s)" – Section Cognitive Science), 4*.

Purcell, J. J., Turkeltaub, P. E., Eden, G. F., & Rapp, B. (2011). Examining the central and peripheral processes of written word production through a meta-analysis. *Frontiers in Psychology, 2*, 239.

Qu, Q., Damian, M. F., Zhang, Q., & Zhu, X. (2011). Phonology contributes to writing: Evidence from written production in nonalphabetic language. *Psychological Science, 22*(9), 1107–1112.

Rapp, B. C., Benzing, L., & Caramazza, A. (1997). The autonomy of lexical orthography. *Cognitive Neuropsychology, 14*, 71–104.

Rapp, B., Epstein, C., & Tainturier, M.-J. (2002). The integration of information across lexical and sublexical processes in spelling. *Cognitive Neuropsychology, 19*, 1–29.

Roux, J.-S., McKeeff, T. J., Grosjacques, G., Afonso, O., & Kandel, S. (2013). The interaction between central and peripheral processes in handwriting production. *Cognition, 127*, 235–241.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition, 55*, 151–218.

Søvik, N., Arntzen, O., Samuelstuen, M., & Heggberget, M. (1994). Relations between linguistic word groups and writing. In C. Faure, G. Lorette, & A. Vinter (Eds.), *Advances in handwriting and drawing: A multidisciplinary approach* (pp. 231–246). Paris: Europia.

Sprenger-Charolles, L. (2003). Reading acquisition: Cross linguistic data. In T. Nunes & P. Bryant (Eds.), *Handbook of children's literacy*. Kluwer Academic Publishers.

Teulings, H.-L., Thomassen, A. J. W. M., & Van Galen, G. P. (1983). Preparation of partly precued handwriting movements: The size of movements units in handwriting. *Acta Psychologica, 54*, 165–177.

van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10*, 165–191.

van Galen, G. P. (1993). Handwriting: A developmental perspective. In A. F. Kavelboer, B. Hopmkins, & H. Geuze (Eds.), *Motor development in early and later childhood: Longitudinal approaches* (pp. 217–228). Cambridge: Cambridge University Press.

van Galen, G. P., Meulenbroek, R. G. J., & Hylkema, H. (1986). On the simultaneous processing of words, letters and strokes in handwriting: Evidence for a mixed linear and parallel model. In H. S. R. Kao, G. P. van Galen, & R. Hoosain (Eds.), *Graphonomics: Contemporary research in handwriting*. Amsterdam: North-Holland.

van Galen, G. P., Smyth, M. M., Meulenbroek, R. G. J., & Hylkema, H. (1989). The role of short-term memory and motor buffer in handwriting under visual and non-visual guidance. In R. Plamondon, C. Y. Suen, & M. L. Simner (Eds.), *Computer recognition and human production of handwriting* (pp. 253–271). London: World Scientific Publications Co Pte Ltd.

Zesiger, P., Mounoud, P., & Hauert, C. A. (1993). Effects of lexicality and trigram frequency on handwriting production in children and adults. *Acta Psychologica, 82*, 353–365.

Zhang, Q., & Damian, M. F. (2010). Impact of phonology on the generation of handwritten responses: Evidence from picture-word interference tasks. *Memory & Cognition, 38*, 519–528.

Ziegler, J., Jacobs, A., & Stone, G. (1996). Statistical analysis of the bi-directional inconsistency of spelling and sound in French. *Behavior, Research Methods, Instruments, & Computers, 28*, 504–515.