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Pauline Quemart, Eric Lambert

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The Influence of the Morphological Structure of Words on the Dynamics of Handwriting in Adults and Fourth and Sixth Grade Children

Pauline Quémart[1*] and Eric Lambert[1]

[1] Université de Poitiers, Université de Tours, Centre National de la Recherche Scientifique and Centre de Recherches sur la Cognition et l'Apprentissage (CeRCA)

*Address for correspondence

Pauline Quémart

Centre de Recherches sur la cognition et l'apprentissage (CeRCA) - UMR CNRS 7295

Maison des Sciences de l'Homme et de la Société (MSHS)

5, rue Théodore Lefebvre

TSA 21103 F-86073 Poitiers CEDEX 9 France

Tel: (+33)(0)5 49 45 46 19 ; Fax: (+33)(0)5 49 45 46 16

E-mail: pauline.quemart@univ-poitiers.fr

Abstract

Grapheme and syllable units have been shown to influence the dynamics of handwriting in adults and children, but the influence of morphemes remains to be clarified. We tested the ability of French-speaking adults and fourth and sixth grade children to process the morphological structure of words during writing. They were asked to copy three types of words on a digitizer: morphologically complex words, morphologically simple words matched for the bigram at the syllabic boundary, and morphologically simple words matched for the bigram at the morphemic boundary. Latencies were shorter for morphologically complex words than for simple words only in adults. Requiring individuals to process morphological structure increased the time taken to write the letter before a morphemic boundary in adults and sixth graders. In contrast, fourth graders wrote the letter before the syllabic boundary more quickly for complex words than for simple words. These results indicate that words are represented in a decomposed form in the lexicon, and that the morphological structure of words regulates the dynamics of handwriting.

Keywords: Handwriting; morphology; copy task; French

Abstract word count: 169 words

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Handwriting is a complex task that requires coordination of the brain, eyes, and fingers. The spatial and temporal aspects of handwriting are influenced by peripheral motor processes (i.e., coordination and control of the motor gesture), but also by central linguistic processes (e.g., semantic activation, spelling retrieval, Purcell, Turkeltaub, Eden, & Rapp, 2011; Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013). Several units such as bigrams or syllables have been shown to influence adults' handwriting in alphabetic orthographies (Álvarez, Cottrell, & Afonso, 2009; Kandel, Álvarez, & Vallée, 2006; Kandel & Spinelli, 2010; Sausset, Lambert, Olive, & Larocque, 2012), but the influence of morphemes has hardly been studied. Given the central role of morphemes in the acquisition and in the processing of written language (Amenta & Crepaldi, 2012; Verhoeven & Carlisle, 2006), further investigation is needed. The aim of this study was to determine whether adults and fourth and sixth grade children process morphologically complex words through their smaller components during handwriting.

The format of the representation of words in the lexicon is a long-standing subject of debate in psycholinguistics (e.g., Taft, 2015). In addition, the nature of the units activated during writing is currently in the spotlight. The linguistic units processed during spelling directly influence the dynamics of handwriting. Van Galen's (1991) model of handwriting proposes that central levels of processing (and more specifically the spelling level) are activated in parallel with peripheral levels of processing (such as the activation of motor programs). This parallel activation leads to a cognitive load, increasing movement duration and the duration of pauses (for a review, see Olive, 2014). Therefore, examining the dynamics of handwriting provides valuable information about the units processed during written word production.

In Van Galen's (1991) model, orthographic representations of words are stored in a spelling module (see also Kandel, Peereman, Grosjacques, & Fayol, 2011). However, he did not describe precisely the nature of the units represented within this module that directly influence the dynamics of handwriting. In this study, we examined whether the orthographic representations are structured around whole words or morphemes, and how these representations influence handwriting.

The influence of morphemes on lexical access and lexical representations has been widely studied in the field of visual word recognition over the past 40 years (e.g., Marslen-Wilson, Tyler, Waksler, & Older, 1994). Morphemes are the smallest units of meaning in a language. There are two types of morphemes: free morphemes, also called base words, that function as words without needing to be attached to other morphemes (e.g., *nation*) and bound morphemes, also called prefixes and suffixes (e.g., *re*-, *un*-, -*al*, -*ier*, etc.), that are added to base words to create morphologically complex words (e.g., *national*). Bound morphemes can be derivational or inflectional. Derivational morphemes make it possible to form a new word on the basis of an existing one, whereas inflectional morphemes indicate grammatical information (tense, gender, number, etc.).

Many alphabetic writing systems – including French – represent morphological information. Seventy-five percent of French words are morphologically complex and can be broken down into smaller units (Rey-Debove, 1984) and French orthography often preserves morphological information at the expense of phonological information. For example, many French words have a final letter that is not pronounced but attests to the word's relationship to morphologically related *words (e.g., chat* [cat] → *chatte*, *chaton*, *chatière* [female cat, kitten, cat flap]). Therefore, there are good reasons to expect morphology to play a key role in the processing of written language.

An important number of studies have shown that morphological information facilitates lexical access during visual word recognition (Longtin, Segui, & Hallé, 2003; Rastle, Davis, & New, 2004; Taft & Forster, 1976; for a review, see Amenta & Crepaldi, 2012). For example, primes consisting of morphologically complex words (i.e., words composed of at least two morphemes, e.g., *employer*) lead to faster recognition of related targets (e.g., *employ*) than unrelated primes (e.g., *addition*) (e.g., Rastle & Davis, 2008). Such facilitation reflects the activation of a morphological level of representation in the lexicon (e.g., Marslen-Wilson et al., 1994) that speeds up lexical access.

By contrast, there is only scant empirical evidence that written word production is also regulated by morphemes. Neuropsychological data suggest that morphemes may serve as processing units in handwriting production. Badecker, Hillis, and Caramazza (1990) reported the case of patient DH, who made fewer errors when writing morphologically complex words than when writing morphologically simple words (i.e., words that constitute one morpheme). They suggested that morphologically complex words may be represented in decomposed form in the orthographic lexicon.

Behavioral studies also provide evidence that morphological processing occurs during handwriting. To our knowledge, only three studies, all relating to French, have investigated this issue in adults. The first one was by Orliaguet and Boë (1993) and involved inflectional morphemes. A sentence was presented orally and participants were required to complete it by providing the correct spelling for the final word. All final words had the same spelling and the same pronunciation in French, but they belonged to different grammatical categories. For example in French '*vers*' means 'towards' when used as a preposition but, when used as a noun, it is also the plural form (with an *s*-ending) of the word '*ver*' which means 'worm'. The sentence context was provided to enable participants to select the appropriate lexical entry. The authors showed that the writing latency and time taken to write the final word were greater if a grammatical rule had to be applied (i.e., adding a final morpheme 's' at the end of '*vers*') than for invariant words (e.g., '*vers*' used as a preposition). They inferred from this result that adult writers activate the noun and its plural form consecutively when performing the writing task. They argued that words are represented in decomposed form in the lexicon, and that the addition of the inflectional suffix to the base requires additional processing time and interferes with the dynamics of handwriting.

Two studies of derivational morphology by Kandel's team expanded on Orliaguet and Boë's study. Kandel et al. (2008) asked participants to copy morphologically complex words (e.g., *boulette* [dumpling]) and morphologically simple words matched for word ending (e.g., *goélette* [schooner]) on a digitizer, in uppercase letters. The results revealed that the interval between two letters (inter-letter interval, ILI) at a morphemic boundary (e.g., the interval between *l* and *e* in *boul_ette*) in a morphologically complex word was longer than the interval between the same two letters in a morphologically simple word (e.g., *l* and *e* in *goél_ette*). Writing latencies were also longer for complex words than for simple words: morphological structure influenced processes occurring before handwriting (i.e., latencies) and during word production (at the morphemic boundary). More recently, using the same task but different materials, Kandel, Spinelli, Tremblay, Guerassimovitch, and Alvarez (2012) showed that the influence of morphemes on the handwriting of complex words can be observed, not only at the morphemic boundary, but also at other locations in the word. Morphological complexity increases ILIs at the syllabic boundary (e.g., between the *u* and the *l* in *boulette* compared with the *o* and the *é* in *goélette*) and it also increases letter stroke duration before the morphemic boundary (the *l* of *boulette* compared to the *l* of *goélette*). No latency effects were reported in this later study. In summary, morpheme constituents modulate adults' handwriting but the precise dynamics need to be further explored.

In this study, we examined the influence of morphemic structure on the dynamics of adults and children's handwriting. It is less clear whether and how central linguistic processes modulate handwriting in the case of children than it is in adults and there have been fewer studies of children's handwriting. As explained above, handwriting is influenced by peripheral motor and central linguistic processes. Grapho-motor automatization is critical because it frees up cognitive resources for other aspects of writing (Berninger et al., 1997; Graham & Weintraub, 1996). When motor transcription is automatic, writers are capable of activating peripheral and central levels of processing simultaneously. However, working memory limitations mean that it is more difficult for children to activate these two levels of processing simultaneously when writing (Olive & Kellogg, 2002). The coordination of writing processes therefore involves the slowing down of motor processes to accommodate cognitive processing demands.

To our knowledge, the influence of morphological structure on children's handwriting has not yet been investigated. However, the role of morphology in literacy acquisition has received increased attention over the past two decades (Carlisle & Goodwin, 2016; Kirby et al., 2012; Nagy, Carlisle, & Goodwin, 2013; Pacton & Deacon, 2008; Quémart, Casalis, & Colé, 2011; Quémart, Casalis, & Duncan, 2012). This interest can be explained by several factors. First, as explained above, most alphabetic writing systems are morphophonemic: they represent both phonemic and morphemic units. In addition, most of the new words that children encounter in print are morphologically complex (Nagy & Anderson, 1984). Therefore, having the ability to decompose these words into morpheme units should help children to retrieve their representation from memory.

There is now clear evidence that children's sensitivity to the morphological structure of words influences literacy acquisition. Children's morphological awareness (the "conscious awareness of the morphemic structure of words and their ability to reflect on and manipulate that structure", Carlisle, 1995, p. 194) grows substantially between the first and the third grade, and continues to grow after the fourth grade (Berninger, Abbott, Nagy, & Carlisle, 2010). Sensitivity to the morphological structure of words explains a significant part of the variance in reading in early primary grades (i.e., grades 1–3; Casalis & Louis Alexandre, 2000; Kirby et al., 2012; for a review, see Kuo & Anderson, 2006) but this contribution is limited when phonological awareness is controlled (Kuo & Anderson, 2006; Singson, Mahony, & Mann, 2000). The proportion of variance explained by morphological awareness increases over the school years (Singson et al., 2000) and remains significant in eighth grade (Roman et al., 2012). Children also process the morphological structure of words when reading. They read morphologically complex words (e.g., *dancer*) more accurately than simple words (e.g., *dinner*) as early as in second grade (Carlisle & Stone, 2005). The presence of a root and/or a suffix facilitates lexical access during visual word recognition from the second grade (Beyersmann, Castles, & Coltheart, 2012; Quémart et al., 2012). When combined to create pseudowords (e.g., *farm-age*), morphemes slow down lexical decisions (Beyersmann, Cavalli, Casalis, & Colé, 2016; Quémart et al., 2012) but make pseudoword naming faster (Burani, Marcollini & Stella, 2002; Colé, Bouton, Leuwers, Casalis, & Sprenger-Charolles, 2012).

Morphemes also influence children's spelling accuracy. In the case of English, second to eighth grade spellers use their knowledge of root spelling (e.g., *turn*) when spelling morphologically complex forms (e.g., *turning*, Carlisle, 1987; Deacon & Bryant, 2006). The morphological structure of words also influences word ending spelling: 6- to 10-year-old children are better able to choose a letter as the correct ending for a word (e.g., *-y*) when it constitutes a suffix (e.g., *lucky*) than when it does not (e.g., *study*) (Sangster & Deacon, 2011). In the case of French, second and fourth graders are better able to report a silent final letter (e.g., the *-d* at the end of *bavard* [chatty]) when the word belongs to a morphological family (e.g., *bavarder*, *bavardage* [chat, chatting]) than when it does not (e.g., *buvard* [blotting paper] which has no derived words, Sénéchal, 2000). French-speaking spellers also benefit from morphological relatedness when they learn to spell new words: eight-year-olds are better able to choose the correct spelling of a pseudoword (e.g., *vensois*) presented in a text if it is associated with other related pseudowords in the story (e.g., *vensoise*, *vensoisiste*) than if it is not (Pacton, Foulin, Casalis, & Treiman, 2013).

Taken together, these findings clearly indicate that children's lexicons are organized around morpheme units, and this level of representation influences literacy acquisition from the beginning of spelling development. However, the extent to which morphological representations modulate the dynamics of handwriting across development remains unknown.

This Study

In the current study, we aimed to explore whether and when the morphological structure of words affects the dynamics of adults' and children's handwriting. Two main types of processes interact at the spelling level during handwriting (Lambert, Kandel, Fayol, & Espéret, 2008). First, the spelling of a word needs to be retrieved from the orthographic lexicon. Second, it needs to be maintained in the orthographic working memory, a temporary buffer that maintains orthographic representations during subsequent serial selection of letter shapes. We make the general assumption that the unit of representation of words in the lexicon is the morpheme (Marslen-Wilson et al., 1994). The retrieval of orthographic representations from the mental lexicon may influence different moments of the writing process (Roux et al., 2013). If the retrieval of morphologically structured orthographic codes occurs before writing execution, it should affect writing latencies. If orthographic retrieval still operates after the initiation of the writing movements, we assume that morphological representations will also affect handwriting at critical locations. The first critical location is the morphemic boundary, i.e., the boundary between two morphemes (e.g., sing/er). The retrieval of the second morpheme may occur when writing the last letter of the first morpheme and/or during the inter-letter interval. The second critical location is the syllabic boundary (e.g., sin/ger). Many studies have pointed out the influence of syllable units on handwriting (in adults: Álvarez et al., 2009; Kandel, Álvarez, et al., 2006; Sausset, Lambert, & Olive, 2013; in children: Kandel & Valdois, 2006a, 2006b; Soler & Kandel, 2012). According to Lambert et al. (2008; see also Service & Turpeinen, 2001), words are maintained syllable by syllable in the orthographic working memory. Therefore, the syllabic boundary is also critical and may be a good moment to retrieve the next morpheme in the lexicon (as already evidenced by Kandel et al., 2012).

We addressed three research questions in the present study (RQs): (1) Do morphemes influence handwriting in children and in adults? (2) At what moment in the handwriting process do morphemes influence the dynamics of written word production? and (3) Does the influence of the morphological structure differ according to the level of expertise in the written language?

To address these issues, we asked children in fourth and sixth grades and adults to perform two tasks. The first task was a *word copy task* on a digitizer. The target words were divided into three different categories: morphologically complex words, i.e., those built from a base word and a derivational suffix (e.g., *fe**r.m_i**er* [farmer]; the dot corresponds to the syllabic boundary and the underscore to the morphemic boundary); morphologically simple words matched to the morphologically complex words with respect to the bigram at the syllabic boundary (e.g., *fo**r.m**ule* [formula]); morphologically simple words matched to the morphologically complex words with respect to the bigram at the morphemic boundary (e.g., *che**m_i**se* [shirt]).[1] This design made it possible to compare directly the writing duration of the

[1] Note that we included these two control conditions because the constraints of the French language did not make it possible to match the control words simultaneously for the bigram at the syllabic boundary and at the morphemic boundary.

same letters according to the morphological construction of words (RQ1) and to locate morphological processing at different moments in word writing (before beginning to write, around the syllabic boundary, and the morphemic boundary) through various measures: latencies, letter durations, and ILIs (RQ2).

The second task was a *naming task* using the same items as in the copy task. This task was used to disentangle the effects on latency due to identification of the target word and those due to the preparation required to produce it. We selected a naming task because the processes involved in this task are comparable to the copying task: They both require a sequential processing of the graphemes, and they do not involve making a decision on the stimuli.

The performances of three groups of participants were examined (RQ3). The inclusion of fourth graders and sixth graders in the experiment was motivated by reasons related (1) to the influence of morphological information on literacy acquisition and (2) to the development of handwriting. We chose to test fourth graders (i.e., children around nine years old) because we wanted to ensure that they would activate morphemes during lexical access. At the same time, grapho-motor processing is sufficiently (but not completely) automatized at this age to observe the influence of central processes on peripheral processes (Hamstra-Bletz & Blöte, 1993; Kandel & Perret, 2015). We also included a group of sixth graders (children around 11 years old) to track possible developmental changes in their ability to process the morphological structure of words when handwriting. In addition, grapho-motor processes are nearly automatized at this stage but they may be less efficient than in adults (Pontart et al., 2013).

We formulated specific hypotheses related to the three RQs. We assumed that fourth and sixth graders would activate the morpheme constituents when writing, and so we expected that children's handwriting would be influenced by the morphological structure of words as early as fourth grade (RQ1). Regarding the location of the morphological effect (RQ2), we predicted that the influence of the morphological structure of words would be observed at different moments in the writing of words. Morphological processing implies the activation of two morpheme units when writing morphologically complex words (the base word and the suffix) and this activation can take place at two moments: Either both morphemes are retrieved in the orthographic lexicon before word initialization, or they are successively activated during word production (interfering with the dynamics of handwriting). If morphemes are retrieved prior to the execution of handwriting we expect latencies to be longer for two-morpheme words than those consisting of a single morpheme (as shown by Kandel et al., 2008; see also Sausset et al., 2012 for syllable processing). In addition, if morphemes are activated during handwriting, the processing involved in doing so should slow down grapho-motor processes around the syllabic boundary and/or around the morphemic boundary (Kandel et al., 2008, 2012).

The current literature on this topic is very limited, so it is difficult to put forward hypotheses regarding the differential effects according to the group (RQ3). In adults, morphological effects have been reported on latencies (Kandel et al., 2008) and on letter durations (Kandel et al., 2012). Therefore, we make the assumption that the morphological structure of words will influence adults' latencies and within-word variables. The data in the literature do not allow us to formulate clear hypotheses about the location of the effects in children. The influence of symbolic units such as syllables and morphemes on the dynamics of handwriting has never been investigated in children. Recent data suggest that their writing latency is influenced by word regularity (Kandel & Perret, 2015) and word frequency (Afonso, Suárez-Coalla, González-Martín, & Cuetos, 2017). The less regular or the less frequent the words are, the more children program their written production before starting to write. Orthographic regularity also modulates the duration and the fluency of the writing movement in 8- to 10- year old children (Kandel & Perret, 2015). These data suggest that both writing latencies and within-word variables can be influenced by spelling activation in children. We make the prediction that morphological information will influence writing latencies and within-word variables.

Material and Methods

Participants

Twenty-five fourth graders (*M* = 10.0 years; *SD* = 0.42), thirty-five sixth graders (*M* = 11.5 years; *SD* = 0.58) and thirty adults (*M* = 23.0 years; *SD* = 2 years) participated in the study. The fourth graders group included 15 girls and 10 boys (23 right-handed and 2 left-handed), the sixth graders group included 19 girls and 16 boys (26 right-handed and 9 left-handed) and the adult group included 24 women and six men (24 right-handed and 6 left-handed). The fourth graders were in their fourth year of explicit reading and writing instruction, and the sixth graders were in their sixth year of reading and writing experience. They were recruited from primary and secondary schools, respectively, near the city of Poitiers, France. Parental consent was obtained before the experiment started. The adult participants were undergraduate students from the University of Poitiers who participated voluntarily and did not receive credit for doing so. All participants were native speakers of French and reported normal or corrected-to-normal vision. The experiment adhered to the ethical guidelines of University of Poitiers in accordance with the Declaration of Helsinki.

Stimuli

Thirty-six bisyllabic French words were selected for the experiment. They were assigned to three conditions: morphological, syllabic control, and morphological control. The mean characteristics of these stimuli are presented in Table 1, and the full set of stimuli is listed in Appendix A.

[Insert Table 1 around here]

Twelve morphologically complex words were used for the morphological condition. They were all made up of a base word and a derivational suffix (e.g., *fermier* [farmer]) and the base word frequency (*M* = 132.11; *SD* = 176.96; lexical frequency taken from the Manulex lexical database, Lété, Sprenger-Charolles, & Colé, 2004) was always higher than whole-word frequency (*M* = 27.16; *SD* = 22.16).

The words used in the syllabic control condition were morphologically simple words matched to the morphologically complex words used in the morphological condition with respect to the bigram at the syllabic boundary (e.g., *fer.mier* was matched to *for.mule*, the dot corresponds to the syllabic boundary). Pairs of words had exactly the same number of letters (*M* = 6.92, *range* = 6–8) and were matched for lexical frequency ($t < 1$) and bigram frequency ($t(22) = 1.20$, $p = .24$).

The words used in the morphological control condition were morphologically simple words matched to those used in the morphological condition with respect to the bigram at the morphemic boundary (e.g., *ferm_ier* was matched to *chem_ise*, the underscore corresponds to the morphemic boundary). Pairs of words from the two conditions also had exactly the same number of letters (*M* = 6.92, *range* = 6–8) and were matched for lexical frequency ($t < 1$) and bigram frequency ($t(22) = 1.20$, $p = .24$).

Procedure and Apparatus

Participants were tested individually. The participants sat in a quiet room at a comfortable viewing distance from the screen. All participants performed the naming task first.

Naming task. Stimulus presentation and data collection were controlled using DMDX 3.0 (Forster & Forster, 2003) running on a Dell Latitude E6500 laptop computer. Responses were recorded on a microphone and recordings were made using the RecordVocal function of DMDX.

Each trial consisted of a sequence of two events. First, a fixation cross (+) was displayed in the middle of a screen. Then the participant had to press the space bar to make the target word appear on the computer screen. The stimuli were presented in 50-point Calibri font. The participant then had 5000 ms to pronounce the word after which a new fixation cross appeared. Participants performed six practice trials before the experimental stimuli were presented.

Copying task. The experiment was run on a Dell Latitude E6500 laptop computer. Stimulus presentation and digital recording of the responses were controlled by Eye and Pen© (Alamargot, Chesnet, Dansac, & Ros, 2006). Words were presented in uppercase, 50-point Calibri font in the center of the computer screen. The participants' responses were recorded by a Wacom Intuos 3 graphic tablet and a Wacom inking pen. A sheet of A5 paper marked with five lines was attached to the tablet. Stickers were positioned at the left (left sticker) and right (right sticker) boundaries of each line. The lines and stickers were vertically aligned and the two stickers were horizontally aligned.

A trial consisted of a sequence of four events. First, the participant triggered the presentation of a stimulus by pressing with the pen on the left sticker. Second, the stimulus appeared on the computer screen. Third, the participant wrote the word in uppercase letters on the sheet of paper. The stimulus disappeared from the screen as soon as the participant started to write to prevent him or her from looking back at the target word. Fourth, the participant pressed on the right sticker to indicate that he or she had finished writing.

To familiarize them with the digitizer, participants were asked to write their first name, their grade level, and their birth date on the first sheet. They then performed six practice trials (the same training stimuli as in the naming task) before the experimental trials began.

Results

Data Analysis

We assessed the influence of word construction and grade on six variables. Data for two variables were recorded before word production: oral naming latency (the delay between the appearance of the stimulus on the screen and the start of oral naming) and writing latency (the delay between the appearance of the word on the screen and the first pen press on the digitizer). Four variables were recorded during word production: Letter writing duration before the syllabic boundary, ILI at the syllabic boundary, letter writing duration before the morphemic boundary, ILI at the morphemic boundary. Letter writing duration was measured between the onset of the target letter (pressure > 0) and the end of this letter (pressure = 0). ILI was defined as the period during which two letters were separated by a pen lift. It was measured between the end of one letter (pressure = 0) and the onset of the next (pressure > 0).

Children's and adults' data were analyzed separately because the variances were not homogeneous. Grade (two levels: fourth grade; sixth grade) was treated as a between-subjects variable in children, and word construction (simple; complex) was treated as a within-subjects factor in both children and adults. For latencies measures, we added the task (two levels: naming vs. copying) as a within-subject factor.

Table 2 shows the means for naming and writing latencies, letter-writing duration and ILI by condition and group. To analyze the effect of morphological structure on naming and writing latencies, we compared morphologically complex words with morphologically simple words (independently of the type of matching). We used two comparisons to analyze the effect of morphological structure on the dynamics of handwriting to ensure that we were always comparing identical bigrams. (1) We compared mean letter-writing duration for the pre-boundary letter and mean ILI at the syllabic boundary in morphologically complex words with the letter-writing duration and ILI for the same unit embedded in a morphologically simple word (e.g., *fer.mier* vs. *for.mule*). (2) We compared mean letter-writing duration for the pre-boundary letter and mean ILI at the morphemic boundary in morphologically complex words with the letter-writing duration and ILI for the same unit embedded in a morphologically simple word (e.g., *ferm_ier* vs. *chem_ise)*.

We ran linear mixed-effects models (Baayen, Davidson, & Bates, 2008) as this made it possible to analyze both group and condition effects in a single analysis. We used a hierarchical structure, with items nested within participants. Because the data were positively skewed they were subjected to a log transformation. Data for incorrect responses (4.38%) and outliers (4.55%) were excluded from analysis.

[Insert Table 2 around here]

Adults' Results

Latencies. Latencies were faster for the naming task than for the copying task, $F(1, 2079) = 10{,}343.84$, $p < .001$, but they were not influenced by morphological structure ($F < 1$). Importantly, the interaction between task and morphological structure was significant, $F(1, 2079) = 13.70$, $p < .001$. Morphological structure did not influence naming latency, $F(1, 2079) = 12.24$, $p = .13$ but writing latencies were longer for morphologically simple words than morphologically complex words, $F(1, 2079) = 4.62$, $p = .032$.

Within-word writing variables at the syllabic boundary. Morphological structure did not affect the time taken to write the letter preceding the syllabic boundary, $F(1, 729) = 2{,}25$, $p = .134$, or the ILI, $F(1, 729) < 1$.

Within-word writing variables at the morphemic boundary. It took longer to write the letter preceding the morpheme boundary in morphologically complex words than morphologically simple words, $F(1, 729) = 4.86$, $p = .028$. Finally, morphological structure did not affect the ILI at the morphemic boundary, $F(1, 729) < 1$.

Summary of Adults' Results

In adults, morphological structure influences handwriting at two locations. First, writing latency is shorter for morphologically complex words than for simple words. Second, letter-writing duration for the letter before the morphemic boundary is longer for morphologically complex words than simple words.

Children's Results

Latencies. Latencies were faster for the naming task than the writing task, $F(1, 4291) = 1683.11$, $p < .001$. The main effect of the grade and the main effect of the morphological construction were not significant (*F*s < 1) and the interactions between these variables were not significant either (*F*s < 1).

Within-word writing variables at the syllabic boundary. Letter-writing duration was longer in fourth graders than sixth graders, $F(1, 1{,}350) = 4.03$, $p = .045$, but there was no effect of morphological structure on letter-writing duration, $F(1, 1{,}350) = 1.48$, $p = .224$. There was an interaction between grade and morphological structure, $F(1, 1{,}350) = 145.3$, $p < .001$. Planned comparisons showed that letter-writing duration for the letter preceding the syllabic boundary was longer in morphologically simple words than morphologically complex words in fourth graders, $F(1, 1{,}350) = 5.61$, $p = .018$, but not in sixth graders, $F(1, 1{,}350) < 1$.

ILI was not affected by grade, $F(1, 1{,}350) < 1$, or morphological structure, $F(1, 1{,}350) < 1$. There was an interaction between grade and morphological structure, $F(1, 1{,}350) = 101.5$, $p < .001$, but morphological structure did not affect ILI in fourth graders, $F(1, 1{,}350) = 1.750$, $p = .186$, or sixth graders, $F(1, 1{,}350) < 1$.

Within-word writing variables at the morphemic boundary. Letter-writing duration for the pre-boundary letter was longer in fourth graders than in sixth graders, $F(1, 1{,}350) = 5.396$, $p = .020$. Letter-writing duration was marginally longer for morphologically complex words than morphologically simple words, $F(1, 1{,}350) = 3.612$, $p = .058$. There was an interaction between grade and morphological structure, $F(1, 1{,}350) = 9.136$, $p = .003$. Planned comparisons showed that letter-writing duration for the pre-boundary letter was longer for morphologically complex words than for morphologically simple words in sixth graders, $F(1, 1{,}350) = 4.333$, $p = .0.38$, but not in fourth graders, $F(1, 1{,}350) = 2.585$, $p = .108$.

Finally, there was no effect of grade, $F(1, 1{,}350) < 1$, and no effect of morphological structure, $F(1, 1{,}350) < 1$, on ILI at the morphemic boundary. There was an interaction between grade and morphological structure, $F(1, 1{,}350) = 7.012$, $p < .008$, but morphological structure did not affect ILI in fourth graders, $F(1, 1{,}350) < 1$, or in sixth graders, $F(1, 1{,}350) < 1$.

Summary of Children's Results

The morphological structure did not significantly affect copy latency for children. Fourth graders took longer to write the letter preceding a syllabic boundary when the word was morphologically complex than when it was morphologically simple. In sixth graders, the influence of morphological structure was detectable at the morphemic boundary: pre-boundary letter-writing duration was longer for morphologically complex words than for simple words.

Discussion

The experiment reported here was designed to determine whether and when the morphological structure of words influences the dynamics of handwriting in adults and in children. To this end, we asked adult writers and fourth and sixth grade children to perform a copying task on a digitizer. The target words were morphologically complex (e.g., *fermier* [farmer]), morphologically simple words matched with respect to syllabic boundary (e.g., *formule* [formula]), and morphologically simple words matched with respect to morphemic boundary (e.g., *chemise* [shirt]). We assumed that morphological processing of words would interfere with the dynamics of handwriting in all groups, leading to longer writing latencies, longer letter-writing durations and/or longer ILIs at critical boundaries.

The main findings can be summarized as follows. First, in adults we observed shorter latencies for morphologically complex words than for simple words in the copying task; this difference was not significant in the naming task. Second, the moment at which morphological structure influenced execution of handwriting differed according to group. In fourth graders, letter-writing duration at the syllabic boundary was shorter for morphologically complex words than for morphologically simple words, but morphological structure did not affect letter-writing duration for the letter at the morphemic boundary. In contrast, morphological structure did not affect letter-writing duration at the syllabic boundary in sixth graders or adults, but letter-writing duration for the letter preceding the morphemic boundary was longer in the case of morphologically complex words.

These results clearly indicate that children's and adults' handwriting is influenced by the morphological structure of the words. These results reinforce the idea that words are represented in a decomposed form within the orthographic lexicon, and indicate that word spelling is transferred morpheme by morpheme from the lexicon to the orthographic working memory. Morphological processing interferes with grapho-motor processing, and the location at which this interference is observed is different in adults and children. Below we discuss the implications of these results for our three research questions and for current models of handwriting.

The first research question was concerned with the influence of morphemes on handwriting in children and in adults. There is now clear evidence that morphological information influences children's visual recognition of words (Beyersmann, et al., 2012; Burani et al., 2002; Deacon, Whalen, & Kirby, 2011; Quémart et al., 2011) and their spelling (Deacon & Bryant, 2006; Pacton et al., 2013; Treiman & Cassar, 1996). However, the extent to which morphological processing interferes with children's handwriting has not been investigated before. Here we provide the first evidence that fourth and sixth graders do activate morphological information during handwriting, and that this modulates the dynamics of their handwriting. We also observed that morphological structure influenced adults' handwriting, corroborating earlier reports of this (Kandel et al., 2008, 2012; Orliaguet & Boë, 1993).

The second research question concerned the location at which handwriting morphemes influence the dynamics of written word production. This issue was related to a third research question that concerned the influence of the level of expertise in the written language on the location of these effects in children and in adults. There is now clear evidence of a functional interaction between central and peripheral processing in adults (Roux et al., 2013) and in children (Kandel & Perret, 2015) when processing graphemes and syllables, but it remains unclear what happens in the case of morphemes. In this study, we observed that morphological structure influenced the handwriting process at two different moments in adults: before and during execution of handwriting. In children, the influence of the morphological structure was observed during handwriting, and the location at which this influence was detected varied according to grade.

Writing latencies were shorter for complex words than for simple words in adults. This effect was not evidenced in the naming task, suggesting that the effect was specific to written production. The finding that the latency for written production of words was shorter for complex words than for simple words was unexpected. If the orthographic representations are organized around morphemes, the retrieval of two morphemes when producing morphologically complex words should delay initiation of the motor actions of writing complex words relative to simple words (Kandel et al., 2008). We did not predict that writing latency would be shorter for complex words.

Several distinct processes occur during the delay before the execution of the motor actions required to copy a word. The first is *recognition*: a word is presented visually on the computer screen and the participant activates a representation of that word in his or her orthographic lexicon in order to write it down. The second process is *word spelling retrieval*: Once words are retrieved in the orthographic lexicon, abstract letter identities are sent to orthographic working memory before being written (Caramazza, Miceli, Villa, & Romani, 1987; Hillis & Caramazza, 1989; Rapp, Purcell, Hillis, Capasso, & Miceli, 2015). Finally, latencies are also influenced by a third kind of process: *Motor programming and preparation* (van Galen, 1991).

In this study, the differences in writing latency for the two types of word cannot be attributed directly to recognition processes. Indeed, the comparison of oral and written latencies showed that the morphological structure of words only influenced written latencies, while both tasks involved a recognition process. Oral word naming may nonetheless have influenced written naming indirectly: The activation of lexical units (whole word and base word) during oral naming may indeed influence subsequent written naming. Our results do not allow to conclude on this possible indirect influence since all the participants performed the two tasks.

In addition, there is no reason for motor programming and preparation to be affected by the morphological structure of words in the present study. Words were matched for the initial letter frequency as well as for the initial bigram frequency across the conditions (*F*s <

1), two factors that may influence motor programming and preparation (Kandel et al., 2011; van der Plaats & van Galen, 1990).

The influence of morphological structure may occur at the word spelling level. First, task complexity may modulate the locus of the influence of orthographic representations on handwriting. The more constraining a task, the more delayed are the effects of higher levels on the grapho-motor gesture (Delattre, Bonin, & Barry, 2006; Sausset et al., 2012). Writing two units (in the case of morphologically complex words) increases task complexity, compared to the writing of a single unit (in the case of morphologically simple words). The activation of two morpheme units may therefore slow down word production during handwriting, rather than slowing down writing latencies. The significant influence of morphological construction on letter writing duration corroborates this hypothesis. A second interpretation is related to morpheme length and frequency. If morphemes are sent sequentially from the orthographic lexicon to the orthographic working memory, writing latency should be mainly affected by the activation of the first morpheme. The first morpheme of the morphologically complex words (e.g., *ferm* in *fermier*) was shorter (mean number of letters = 3.75) and more frequent (mean frequency = 132.11) than the morpheme making up the matching morphologically simple words in the syllabic and morphological control conditions (e.g., *chemise*, mean number of letters = 6.92 and mean frequency = 35.33 and 42.24, respectively). The difference in writing latency may therefore be attributed to faster retrieval of the spelling of the short and frequent base word than the longer and less frequent morphologically simple word (Bonin & Fayol, 2002; Bonin, Laroche, & Perret, 2016; van der Plaats & van Galen, 1990). Additional studies are needed to investigate whether and how base word frequency influences writing latencies.

Morphological structure did not influence writing or naming latencies in children. Difficulty with the coordination of central and peripheral levels of processing may lead children to start writing while they are processing the units. It has already been shown that, in adults, a high cognitive load delays the influence of spelling on grapho-motor processes (Sausset et al., 2012), shifting it from the preparatory phase (detectable in writing latency) to the execution phase (detectable in in-word variables). We should nonetheless be cautious when interpreting this absence of effect: It may result from a lack of statistical power due to the sample size or the number of items. Future studies should further examine the conditions under which fourth graders program morphologically complex words before beginning to write.

The third research question was concerned with the effect of print expertise. Morphological structure influenced word production in all three groups of participants. In sixth graders and adults, the time needed to write the letter preceding the morphemic boundary (e.g., the *m* in *ferm_ier*) was longer than the time needed to write the same letter at the same position in a morphologically simple word (e.g., the *m* in *chemise*). Kandel et al. (2012) also reported that, in adults, the stroke duration for the letter preceding the morphemic boundary is longer for morphologically complex words compared to simple words. In their study, ILI durations also tend to be longer in the case of morphologically complex words. Thus, within-word variables were influenced by the morphological structure of words in both studies. This effect can be interpreted as the cascaded influence of central processes on grapho-motor processes (Roux et al., 2013). Sixth graders and adults process the suffix to be written during the production of the preceding morpheme, more specifically during the production of its last letter. These two results indicate that processing of spelling and grapho-motor execution processes occur in parallel. Evidence of this kind of parallel processing has already been provided by Van Galen (1991), and it is a consequence of grapho-motor automatization in adults and sixth graders.

However, the location of the morphological influence within words differed in the two studies. Unlike Kandel et al. (2012), we found no evidence that letter-writing duration or ILI at the syllabic boundary were longer for complex words than for simple words in adults, and the same pattern was observed in sixth graders. Morphological processing does not seem to be as anticipated in our study as it was in the study by Kandel et al. (2012). One explanation for this may be that, in the study by Kandel et al., an additional cognitive load might have been induced because base words were less frequent and hence it was more difficult to retrieve their spelling in the orthographic lexicon. In addition, morphological processing increased writing duration of the letter preceding the morphemic boundary, which was also reported by Kandel et al. (2012). This result suggests that adults and sixth graders activate the next morpheme during their writing of the letter preceding this morpheme. Finally, ILIs at the morphemic boundary were significantly longer (Kandel et al., 2008) or tended to be longer (Kandel et al., 2012) for complex words than for simple words. We did not replicate this result in the present study but, again, we are not able to draw conclusions here from these nonsignificant results.

The influence of morphological structure on fourth graders' handwriting differs from its influence on that of sixth graders and adults. In this group, the writing time for the letter preceding the syllabic boundary was shorter for morphologically complex words than for simple words (e.g., the letter *r* in *fer.mier* vs. in *for.mule*) whilst morphological structure did not influence the time taken to write the letter preceding the morphemic boundary (p = .108). This pattern of results may reflect a syllabic processing of morphologically simple words, leading to longer letter writing time for the letter preceding the syllabic boundary, while writing processes are not slowed down at the syllabic boundary for morphologically complex words. The influence of central processes on grapho-motor processes may occur later in word writing, more specifically at the morphemic boundary. The processing of morphemes may also have an impact on several aspects of the dynamics of handwriting, leading to a globally greater overload that does not differ significantly between both types of words.

Taken together, these results suggest that children's and adults' orthographic lexicons are organized around morpheme units. Morphologically complex words are represented in terms of their constituent morphemes – rather than as whole units – in the orthographic lexicon, hence the activation of morphological units influences the dynamics of handwriting. Current models of visual recognition of words tend to include a morphological level of representation (e.g., Grainger & Ziegler, 2011) but, so far, models of written word production (Kandel et al., 2011; van Galen, 1991) have not incorporated the influence of morphological units. This puts them in conflict with neuropsychological data from dysgraphic patients (Badecker et al., 1990) and experimental data in adults (Kandel et al., 2008, 2012; Orliaguet & Boë, 1993) showing that morphological structure influences handwriting. As explained in the introduction, Van Galen (1991) proposed that the spelling module includes word units. We propose here that organization at the word level is based on morphology, and that word spelling is recovered through the morphological constituents of words rather than through the activation of the whole word. The morphological level of processing is presented in Figure 1. This processing unit is additional to the two other units that have already been shown to influence adults' and children's handwriting: graphemes (Kandel, Soler, Valdois, & Gros, 2006) and syllables (Kandel et al., 2011; Lambert et al., 2008). The influence of morphemes cascades down through the handwriting process in both adults and children. The activation of constituent morphemes is not completed before motor production begins and it continues to influence handwriting during motor production. In sixth graders and in adults the second morpheme of morphologically complex words is preferentially activated during the writing of the last letter of the preceding morpheme, whereas the location of this influence remains unclear in fourth graders.

[Insert Figure 1 around here]

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Figure 1.

Adaptation of Kandel et al.'s (2011) model of handwriting production showing morphemes as a processing level

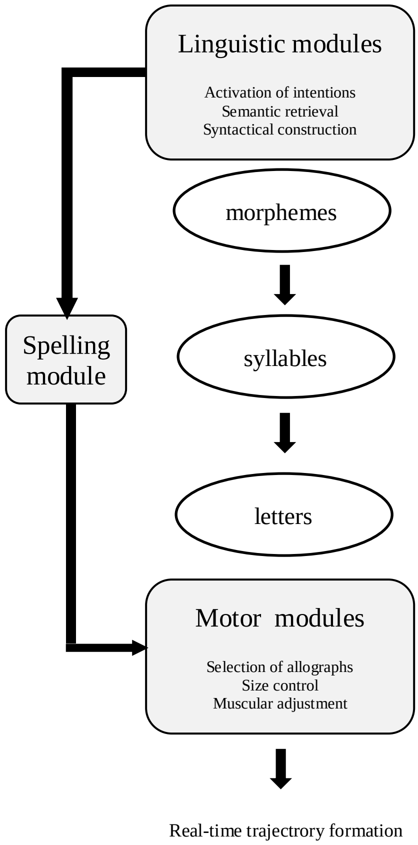

Table 1.

Stimulus properties across test conditions (standard deviations are in parentheses).

Condition	Example	N	Number of letters	Lexical frequency	Summed bigram frequency
Morphological	Fer.m_ier (“farmer”)	12	6.92 (0.51)	27.16 (22.16)	1420.06 (435.01)
Syllabic control	For.mule (“formula”)	12	6.92 (0.51)	35.33 (52.93)	1341.28 (618.12)
Morphemic control	Chem_ise (“shirt”)	12	6.92 (0.51)	42.24 (53.02)	1790.37 (973.87)

Note. Lexical frequency and bigram frequency are given by the French database *Manulex Infra* (Peereman et al., 2007).

Table 2.

Mean (standard deviations in parentheses) naming and writing latencies, letter-writing durations and inter-letter intervals (ILIs) in ms as a function of morphological structure (simple or complex) and group (grade 4; grade 6; adults)

			Syllabic boundary		Morphemic boundary	
Morphological structure	Naming Latency	Writing Latency	Letter-writing duration	ILI	Letter-writing duration	ILI
Grade 4						
Simple	848 (429)	1876 (1123)	692 (391)	441 (319)	740 (340)	384 (311)
Complex	885 (420)	1961 (1269)	641 (318)	428 (318)	767 (382)	388 (330)
Grade 6						
Simple	740 (330)	1806 (1251)	593 (328)	401 (309)	640 (321)	373 (329)
Complex	737 (280)	1802 (1294)	594 (300)	419 (329)	680 (382)	378 (265)
Adults						
Simple	498 (120)	1034 (165)	380 (141)	142 (94)	377 (98)	129 (78)
Complex	514 (123)	1011 (159)	369 (153)	141 (98)	391 (129	128 (78)

Appendix A

Words used in the Experiment (English translations are given in parentheses).

Morphologically complex	Morphologically simple matched with respect to syllabic boundary	Morphologically simple matched with respect to morphemic boundary
Bordure (border)	Sardine (sardine)	Pendule (clock)
Drapeau (flag)	Trapèze (trapezium)	Serpent (snake)
Fermier (farmer)	Formule (formula)	Chemise (shirt)
Plateau (plate)	Platane (plane tree)	Content (happy)
Poirier (pear tree)	Spirale (spiral)	Pluriel (plural)
Pommier (apple tree)	Commode (chest of drawers)	Marmite (cooking pot)
Quartier (quarter)	Pourtant (yet)	Question (question)
Sagesse (wisdom)	Cagoule (hood)	Légende (legend)
Tapage (uproar)	Rapide (rapid)	Rapace (raptor)
Terrier (terrier)	Serrure (lock)	Sourire (smile)
Toiture (roofing)	Guitare (guitar)	Coutume (custom)
Voleur (thief)	Solide (solid)	Soleil (sun)