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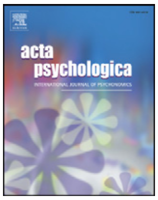

# Processing prefixes and suffixes in handwriting production[☆]

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ABSTRACT

Previous research showed that handwriting production is mediated by linguistically oriented processing units such as syllables and graphemes. The goal of this study was to investigate whether French adults also activate another kind of unit that is more related to semantics than phonology, namely morphemes. Experiment 1 revealed that letter duration and inter-letter intervals were longer for suffixed words than for pseudo-suffixed words. These results suggest that the handwriting production system chunks the letter components of the root and suffix into morpheme-sized units. Experiment 2 compared the production of prefixed and pseudo-prefixed words. The results did not yield significant differences. This asymmetry between suffix and prefix processing has also been observed in other linguistic tasks. In suffixed words, the suffix would be processed on-line during the production of the root, in an analytic fashion. Prefixed words, in contrast, seem to be processed without decomposition, as pseudo-affixed words.

## 1. Introduction

Most research on handwriting has focused on the motor aspects of movement production. From this perspective, writing words would involve the activation of letters, one after the other, in a linear fashion. A further implication of this kind of approach is that the orthographic representations activated for spelling recovery only code information on letter identity and order (Caramazza, Miceli, Villa, & Romani, 1987; Teulings, Thomassen, & Van Galen, 1983; Van Galen, 1991; Van Galen, Smyth, Meulenbroek, & Hylkema, 1989). Thus, the French word *chanteur* ("singer"), for example, would be represented as $C_1H_2A_3N_4T_5E_6U_7R_8$. Recent research has shown, however, that children and adults write words by grouping letters into linguistic-oriented chunks like syllables ($\text{CHAN}_1\text{TEUR}_2$) and complex graphemes ($\text{CH}_1\text{AN}_2\text{T}_3\text{EU}_4\text{R}_5$, Álvarez, Cottrell, & Afonso, 2009; Kandel, Álvarez, & Vallée, 2006; Kandel, Herault, Grosjacques, Lambert, & Fayol, 2009; Kandel, Peereman, Grosjacques, & Fayol, 2011; Kandel & Spinelli, 2010). This tendency to group small units into bigger chunks is a well known phenomenon that is particularly efficient for the memorisation of strings with several elements (cf. Jenkins & Russel, 1952). This writing strategy optimises the recovery of spelling in a phonologically coherent fashion and facilitates the programming of motor outputs (Kandel & Valdois, 2006a, 2006b). Another way of introducing linguistic coherence would be to chunk the word's letters into semantically oriented chunks as morphemes. Morphemes are defined as the smallest units of meaning in the language (e.g., Sandra, 1994). The word *chant* is made up of one morpheme and means "song". If we add the suffix *-eur*, it means "singer". The representation of *chanteur* – a bi-morphemic word – would be more complex than a mono-morphemic word because it would encode the root CHANT and the suffix -EUR, resulting in a representation like $\text{CHANT}_1\text{EUR}_2$. Chunking letters into morphemes could be an efficient way to optimise handwriting programming in French since 75% of the words have more than one morpheme (Rey-Debove, 1984).

Neuropsychological data support the idea that orthographic representations encode information on morphological structure. Baddecker, Hillis, and Caramazza (1990) presented the case of patient DH, who had brain damage that produced a deficit in the graphemic output buffer. This temporary storage device regulates the lexical and non-lexical

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processing of abstract letter representations for spelling tasks and the more peripheral components of the writing sequence. DH mostly produced spelling errors towards the end of words, especially when they were long. However, his performance with morphologically complex words was not merely conditioned by word length. The morphological composition of the word had an effect on the position of the errors: "The affix region of prefixed and suffixed words tended to induce fewer spelling errors than did mono-morphemic, length-matched words (although this effect was more pronounced in the case of suffixes than prefixes)" (Baddecker et al., 1990, p. 233). For instance, in the suffixed word *darkness*, errors were more frequent towards the end of the stem *dark* and decreased on the first letter of the suffix. They then increased towards the end of the suffix. Moreover, morphologically complex words yielded fewer errors than the matched mono-morphemic ones. The authors suggested that morphologically complex words are processed as sequences of morpheme-sized units and are therefore represented in the lexicon in a morphologically decomposed form. This means that the spelling process does not only activate letters, but also roots, prefixes, and suffixes.

The evidence and debate about how morphologically complex words are represented and processed are vast. In the case of word recognition, the proposals range from obligatory pre-lexical decomposition (Taft & Forster, 1976) to models where all kind of words are represented as whole units (Butterworth, 1983). As a compromise between these two positions, dual mechanism models have been proposed that include both whole-word and decomposed representations, depending on the morphological regularity of the words that are being processed (Caramazza, Laudanna, & Romani, 1988). The aim of the present study is to investigate whether morphemes are activated during handwriting production. There has been a considerable amount of research on the influence of morphological structure in perceptual processing (for a review, see Marslen-Wilson, 2007; Rastle, Davis, & New, 2004). However, research on the morphological components of the production counterpart is scarce. Some authors proposed an independent morphological level in speech production processes (e.g., Roelofs & Baayen, 2002; Zwitserlood, Bölte, & Dohmes, 2000). In Roelofs and Baayen's (2002) study, the latencies for morphologically complex words were longer than those for morphologically simple words. In typing, which is also a writing task, morphological structure may regulate the timing of motor production (Weingarten, Nottbusch, & Will, 2004). The morpheme effect was observed when the syllable and morpheme boundaries coincided. The experiments that Weingarten et al. conducted, with German suffixed words, measured the duration of the inter-key interval at the syllable boundary and at the interval between the root and suffix. The authors concluded that "morphemes are processing units measurable in the time course of writing if their boundaries coincide with a syllable boundary" (p. 7).

Two studies conducted in French suggest that the handwriting system could also exploit morpheme-like units. In Orliaguet and Boë (1993), the participants had to write the word *bois* ten times. When this word is mono-morphemic, it means *wood*. When it has two morphemes, it refers to the first person singular form of the verb *boire* and means *(I) drink*. It is the combination of the root of the verb *boire* and the (phonologically silent) flexional suffix (*boi* + *s*). Although *bois* has two meanings, it is always pronounced /bwa/. *Bois* was embedded in carrier sentences that gave contextual information on one of the two meanings (e.g., *ce* ***bois*** *brûle vite* "this wood burns fast" or *je* ***bois*** *de l'eau* "I drink water"). At the end of the carrier sentence, the target word was repeated in isolation and the participant had to write it. The results revealed that latency and movement time were higher when the participants had to write *bois* in a poly-morphemic than a mono-morphemic context. The suffixes used in this experiment were all flexional. The authors explained these differences by saying that the former required more processing than the latter because of application of the conjugation rule.

More recently, Kandel, Alvarez, and Vallée (2008) conducted an experiment in which the participants wrote suffixed and pseudo-suffixed words. They compared the inter-letter interval between the root and suffix in derivational suffixed words (e.g., *boul**ette*** "small ball") with the corresponding serial position in matched pseudo-suffixed words (e.g., *goél**ette*** "caravel"). Pseudo-suffixed words have the same last letters as the suffixed words, but these letters do not have the linguistic function of a suffix. The results yielded longer inter-letter intervals between the root and suffix in suffixed words than in the corresponding position in pseudo-suffixed words.

These duration differences can be explained by the anticipatory conception of handwriting production proposed by Van Galen's (1991) model. The model considers a series of hierarchically organized modules. The first three – activation of intentions, semantic retrieval, syntactic construction – were directly taken from Levelt's (1989) speech production model because they are supposed to be common to speech and handwriting. The differences between speech and handwriting appear at a lower order module, namely the spelling level, where the processing units are words stored as linear sequences of letters containing information on their identity and order. Then, there are three motor modules that process the selection of allographs, size control, and muscular adjustment. All the modules can be active simultaneously, but the higher-order processing levels are always further ahead during the execution of a movement than the lower ones. They anticipate and process information related to forthcoming parts of the word while writing a current sequence. When various levels are active in parallel, and because processing capacities are limited, movement duration increases. The duration increases result from supplementary cognitive loads that are due to the parallel processing of different representational levels. The writing system processes the local parameters (e.g., size, rotation direction, force), on the one hand, and linguistic information on the forthcoming sequences (e.g., morpheme units), on the other. In this context, inter-letter interval durations in Kandel et al. (2008) were longer at the morpheme boundary because the system anticipated the production of the suffix. Van Galen's (1991) model therefore accounts for the duration increases but it cannot explain why we tend to group letters in linguistically oriented chunks when we write (e.g., Kandel et al., 2006 for syllables; Kandel & Spinelli, 2010 for complex graphemes). It considers the orthographic representations of words as linear sequences of letters coding information on letter identity and order.

Kandel et al. (2011) proposed a new model of handwriting production – that is in fact a revision of Van Galen's model – in which the orthographic representation of a word would be a multi-dimensional structure (cf. Caramazza & Miceli, 1990) that codes letter identity and order, of course, but also syllable structure and letter co-occurrences. According to this view, to write a word we activate a representation that also activates syllables and letter components. The syllable module determines the position of grapho-syllabic boundaries. The letter module encodes information about letter co-occurrence (bigram frequency, for example) as well as on the rules that link letters to phonemes (graphemes). These units are then "unwrapped" into their letter constituents. The letter identities are the input for the motor modules that deal with the motor constraints that regulate movement production. The model does not include a morphological processing level because the available data was insufficient.

Kandel et al. (2008) constituted a first attempt to address whether morphological structure constrains handwriting processes, but we considered that the data was not robust enough to include a morpheme level in the model. One limitation of Kandel et al. (2008) was that some of the words that were used as pseudo-suffixed, like *goélette*, were in fact morphologically opaque words instead of pseudo-suffixed words, because *goélette* derives from *goéland* (seagull; see Longtin, Segui & Hallé, 2003 for a discussion on the issue of transparent/opaque affixed words). In the present research, we tried to use better controlled materials in the sense that we made sure that the pseudo-affixed words were not opaque affixed words. Apart from the inter-letter interval duration, an innovation of the present work is that we also measured letter durations. Kandel and colleagues have provided developmental data indicating that the preparation of forthcoming syllables significantly increases the time taken to produce the preceding letters (Kandel & Valdois, 2006a, 2006b; Kandel et al., 2009). Furthermore, Kandel and Spinelli (2010) also used letter duration measures to show that grapheme complexity is processed during the production of letters that are located before the target grapheme. This could apply to morpheme-sized units in adult handwriting production as well. In addition, the present research not only investigated the timing of suffixed word production, but also the processing of prefixed words.

Finally, an interesting contribution of the present study is that we examined the time course of handwriting production by investigating whether morpheme-like units are already active before the morpheme boundary. Studies on typing revealed that the morpheme effect is observed when the syllable and morpheme boundaries coincide (Weingarten et al., 2004). This suggests that processing is done in a cascaded fashion. In handwriting, there is increasing evidence for cascaded processing (Álvarez et al., 2009; Delattre, Bonin, & Barry, 2006; Kandel & Spinelli, 2010; Kandel et al., 2011). These studies have shown that central processes are not completely finished when motor execution starts, and that the representations in the graphemic buffer include graphemic and syllabic information. If morphology is processed in handwriting, would morphological decomposition be planned and finished before motor execution starts or would the effects be observed during writing in later motor stages?

If the representations activated during handwriting production code information on morphological structure, suffixed words (Experiment 1) should be decomposed into root and suffix. Likewise, the activation of prefixed words (Experiment 2) should lead to the programming of two distinct units, namely the prefix and the root. This kind of decomposition should not occur in pseudo-affixed words. This morphological processing should affect the peripheral stages of the motor output, yielding longer movement durations in affixed words than pseudo-affixed words.

## 2. Experiment 1

The purpose of Experiment 1 was to gain understanding on how the writing system deals with the processing of suffixed words. In the study conducted by Weingarten et al. (2004) on German typing, the morpheme effects appeared only when the morpheme and syllable boundaries coincided. To determine whether morpheme processing can take place when it does not coincide with a syllable boundary, we carried out our French experiment with suffixed words where the syllable boundary was always located within the root and before the morpheme boundary.

Kandel et al. (2008) showed that inter-letter interval durations between the root and the suffix were longer than the corresponding position in pseudo-suffixed words. In other words, the processing of the suffix would be carried out after writing the last letter of the root and right before writing the first letter of the suffix. However, previous studies revealed that the writing system operates in a cascaded fashion. It is therefore likely that the processing of the suffix is carried out before the morpheme boundary. Due to the anticipatory nature of the writing process (Van Galen, 1991), we could observe duration increases for suffixed words before this location; i.e., during the production of the root. To address this issue, we had to measure movement duration within the root. It was impossible to constitute an experimental material with the same number of letters in the root for all the words. Since the number of letters of the root of our suffixed words varied from three to five (e.g. *tét**ine*** (pacifier) and *salad**ier*** (bowl), respectively), the only way to measure the same kind of processing during the production of the root in all the words was to focus on the analysis of the syllable boundary. The syllable boundary was located one letter before the morpheme boundary in all the words except four (e.g. *té.t**ine*** and *sala.d**ier***). Furthermore, to examine how morphological processing is done during the production of the root, in addition to measuring inter-letter interval durations as in previous studies, we measured the durations of the letters that preceded the syllable and morpheme boundaries. Fig. 1 presents the predicted activation and programming timing for a suffixed word such as *pruneau*. The word *pruneau* means "prune" and derives from *prune*, which means "plum".

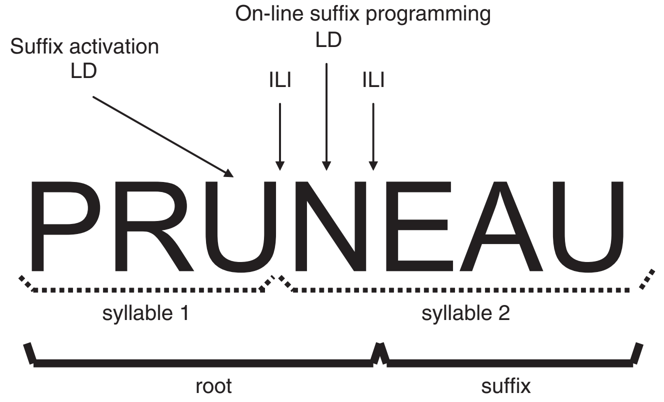

**Fig. 1.** Predicted activation and programming timing for the word *pruneau* at the syllable and morpheme boundaries. LD = letter duration increase, ILI = inter-letter interval duration increase.

Following this example, we expected that the activation of the suffix would be done at the last letter of the first syllable, simultaneously to the production of the U. There should be a processing load at this position, because the handwriting system activates the representation of the suffix, and this processing is done in parallel to the calculation of the U's local parameters (e.g., size and direction), which generates a duration increase (cf. Van Galen's, 1991 model). The duration of the U should thus be longer than the duration of the letter at the same serial position in the pseudo-suffixed word (e.g., *pinceau*, paint brush), where no suffix has to be programmed. After the activation of the suffix, the movement to produce it has to be programmed. This programming would be done on-line, in parallel to the local calculations required to produce the UN interval, the N, and the NE interval. Parallel processing would lead to longer inter-letter intervals and letter durations in suffixed words than the corresponding letter positions in pseudo-suffixed words.

### 2.1. Method

#### 2.1.1. Participants

Forty-three right-handed students from Université Pierre Mendès France participated in the experiment. They were all native French speakers and unaware of the purpose of the experiment. They all had normal or corrected-to-normal vision, and no motor or hearing disorders.

#### 2.1.2. Materials

We selected a total of 46 French words (Appendix A). Half of them were suffixed words (e.g., *prun**eau***, where the suffix is in bold). The words contained various types of derivational suffixes (e.g., *-eau*, *-ine*, *-ette*, *-ier*, *-elle*). We matched these suffixed words to words that shared the same letters as the suffix in the same serial position but that were not suffixed words, namely pseudo-suffixed words (e.g., *pinc**eau***). Thus, for the *pruneau*–*pinceau* pair, the syllable boundary was *pru.neau* for the suffixed word (the dot marks the syllable boundary hereafter) and the corresponding serial position (and syllable boundary) was *pin.ceau* in the pseudo-suffixed word. For the morpheme boundary, we focused on the *ne* area of *prun**eau*** and the corresponding serial position in *pinc**eau*** (i.e., *ce*). Suffixed and pseudo-suffixed words were matched for word frequency. According to the Lexique 2 French Data Base (New, Pallier, Ferrand, & Matos, 2001; http://www.lexique.org), the mean word frequency for suffixed words was 4.26 words per million, and the mean word frequency for pseudo-suffixed words was 6.99 words per million, $t(22)=.73$, $p=.46$. The words were also matched for bigram frequency at the critical positions (see Kandel et al., 2011 for data on the role of bigram frequency in handwriting production). The mean bigram frequency at the syllable boundary for suffixed words was 362, and the mean bigram frequency at the same serial position in the pseudo-suffixed words was 514, $t(22)=1.44$, $p=.16$ (Content & Radeau, 1988). The mean bigram frequency at the morpheme boundary for suffixed words was 692, and the mean bigram frequency at the same serial position in the pseudo-suffixed words was 592, $t(22)=.82$, $p=.41$ (Content & Radeau, 1988; token bigram frequency).

### 2.1.3. Procedure

The experiment was conducted with *Ductus* — a handwriting software package developed in our laboratory for the study of handwriting production (Guinet & Kandel, 2010). At the beginning of each trial, the participants heard an auditory signal and saw a fixation point (for 200 ms) at the centre of a laptop screen. This fixation point was replaced by a word written in upper-case Times New Roman size 18. The participants were asked to write the word they saw as soon as it appeared on the computer screen, and they were instructed to write it at a normal speed. They wrote the word with a special pen (Intuos Inking Pen) on a lined paper (vertical limit = 8 mm, horizontal limit = 17 cm) that was stuck to a digitiser (Wacom Intuos 2, sampling frequency 200 Hz, accuracy 0.02 mm). They were instructed to write the words in upper-case letters and to lift the pen between each letter in a small upward–downward wrist movement. When the participant finished writing a word, the experimenter clicked on a button to present the following word. Prior to the experiment, the participants practised lifting the pen between letters by writing their names several times, until they thought they could do it "spontaneously" for the purposes of the experiment.

We asked the participants to write in upper-case letters instead of their everyday life cursive lower-case letters so that the data analysis would be precise and unambiguous. We intended to measure movement time at different locations within the words (i.e., letter duration and inter-letter intervals; details on the data analysis are provided below). This requires the segmentation of the word into letters. The continuous nature of cursive handwriting makes it difficult to segment a word into letters in a completely unambiguous fashion, especially in adults. With upper-case letters, segmentation is very easy because the digitiser provides precise information on the beginning and end of all the letters in the word. We are aware that Olive and Kellogg (2002) observed that in text composition, the attentional demands are higher when writing in upper-case letters than when writing in cursive letters, but we expected these demands to be much lower when writing isolated words.

The participants wrote the words of Experiments 1 and 2 in a single session. There were 46 items in Experiment 1 and 36 items in Experiment 2. We included 38 fillers that did not share any initial letters with the targets. We presented the 120 words in four blocks of 30 stimuli. The words were randomised across participants. There were two practice items before the beginning of the experimental session. The participants were tested individually in a quiet room. The whole session lasted 40 to 50 min.

### 2.1.4. Data processing and analysis

To obtain the measures on latencies, letter and inter-letter interval durations, we used the data analysis module provided by *Ductus* (Guinet & Kandel, 2010). The data were smoothed with a finite impulse response filter (Rabiner & Gold, 1975) with a 12 Hz cut-off frequency. The duration measure was the time the participants took to write the letter preceding the syllable and the morpheme boundaries. For instance, in *prun**eau***, we measured the time the participant took to write the first *u* because it is the letter that precedes the syllable boundary, and we measured the time he/she took to write the *n* because it is the letter that precedes the morpheme boundary. For the pseudo-suffixed words such as *pinc**eau***, we measured the durations of *n* (syllable boundary) and *c* (pseudo-morpheme boundary). Since we had to compare the durations of letters that are made up of a different number of strokes (e.g., *u* has 2 strokes and *n* has 3 strokes), we normalised the duration values with respect to the number of strokes per letter. There is no standard definition of the number of strokes per letter when writing upper-case letters, as there is for lower-case letters (Meulenbroek & Van Galen, 1990). We thus determined letter segmentation ourselves on the basis of a previous up-stroke/down-stroke analysis of each upper-case letter of the alphabet (see Kandel & Spinelli, 2010; Spinelli, Kandel, Guerassimovitch, & Ferrand, 2011 published on-line, for details on the normalisation procedure). We measured the duration of the inter-letter intervals at the syllable and morpheme boundaries for each word. For example, in *prun**eau***, we measured the interval duration between *u* and *n* for the syllable boundary and between *n* and *e* for the morpheme boundary. For the pseudo-suffixed words such as *pinc**eau***, the syllable boundary interval corresponded to the interval between *n* and *c*, and the pseudo-morpheme boundary to the interval between *c* and *e*. The interval measure was defined as the time period in which two letters were separated by a pen lift. The letter end corresponded to pressure = 0 and the onset of the following letter corresponded to pressure > 0.

## 2.2. Results

This section presents the results for suffixed and pseudo-suffixed words. The results were analysed using linear mixed effects models (Baayen, Davidson, & Bates, 2008; Bates, 2005), which simultaneously take participant and item variability into account. These analyses were performed using the software R with the package lme4 (Bates & Maechler, 2009). The statistical analyses were performed on the letter stroke and interval durations at both the syllable and morpheme boundaries.

### 2.2.1. Letter stroke duration

Fig. 2 presents the mean letter stroke durations for the letter preceding the syllable and morpheme boundaries in suffixed and pseudo-

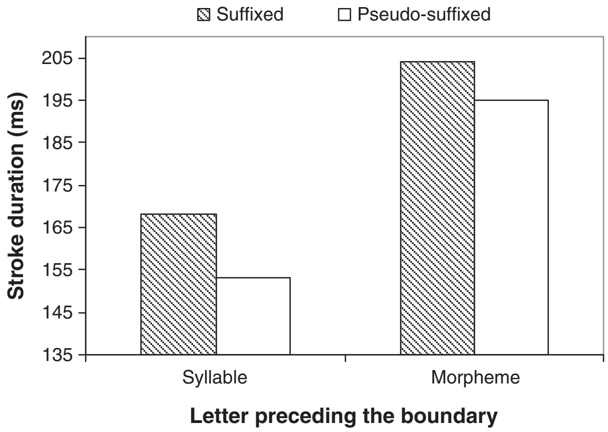

**Fig. 2.** Mean stroke durations (ms) of the letter preceding the syllable and morpheme boundaries for suffixed and pseudo-suffixed words.

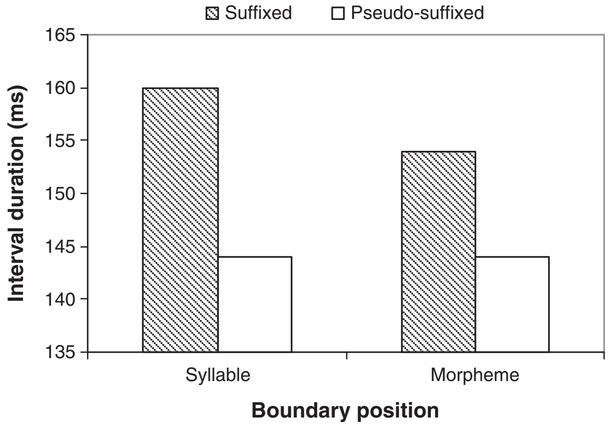

**Fig. 3.** Mean inter-letter interval durations (ms) for suffixed and pseudo-suffixed words at the syllable and morpheme boundaries.

suffixed words. The analyses revealed that the stroke duration for the letter preceding the syllable boundary was longer in suffixed words (e.g., *u* in *pru**neau***) than in pseudo-suffixed words (*n* in *pin**ceau***), $t(1931)=10.24$, $p<.001$. Likewise, the stroke duration of the letter preceding the morpheme boundary was longer in suffixed words (e.g., *n* in *pru**neau***) than the same letter position in pseudo-suffixed words (*c* in *pin**ceau***), $t(1931)=-2.57$, $p<.01$.

### 2.2.2. Interval duration

Fig. 3 presents mean inter-letter interval durations for suffixed and pseudo-suffixed words at the syllable and morpheme boundaries. The analyses indicate that between-syllable intervals were longer in suffixed words (e.g., the interval between *u* and *n* in *pru**neau***) than the same interval in pseudo-suffixed words (e.g., the interval between *n* and *c* in *pin**ceau***), $t(1930)=2.83$, $p<.005$. Between-morpheme intervals were also numerically longer in suffixed words (e.g., the interval between *n* and *e* in *pru**neau***) than the same interval in pseudo-suffixed words (e.g., the interval between *c* and *e* in *pin**ceau***), but the differences did not reach significance, $t(1931)=1.8$, $p=.07$.

## 2.3. Discussion

Experiment 1 examined whether the morphological structure of suffixed words could regulate the timing of handwriting production. The results revealed that the stroke durations of the letters preceding both the syllable and morpheme boundaries were longer in suffixed words than in pseudo-suffixed words. This difference is likely due to a processing load resulting from the processing preparation of the suffix. This does not occur in pseudo-suffixed words because there is no morphological decomposition preparation or segmentation.

The analyses also indicated that the inter-letter intervals were longer for suffixed words than for pseudo-suffixed words at the syllable boundary. At the morpheme boundary, we observed the same trend but the differences did not reach significance. Kandel et al. (2008) found that the interval at the boundary between the root and the suffix was longer than the corresponding interval in pseudo-suffixed words. It is also noteworthy that in German typing tasks, the morpheme effect appeared only when the syllable and morpheme boundaries coincided (Weingarten et al., 2004). In our experiment, the syllable and morpheme boundaries did not coincide. Our data thus reveal that in French, the morpheme effect appears even if syllable and morpheme boundaries do not coincide.

In sum, the data on letter and interval durations indicate that suffixed words were more time-consuming for the writing system than pseudo-suffixed words, suggesting that bi-morphemic words require more processing than mono-morphemic words. The simultaneous processing of suffixes and local parameters seems to overload the writing system at specific locations of the root (cf. Van Galen, 1991). The processing load goes "in crescendo" from the syllable to the morpheme boundary. The information to produce the suffix is already activated when executing the letter preceding the syllable boundary. The programming of the suffix continues during the inter-letter interval at the syllable boundary. This processing is numerically even more time-consuming at the letter preceding the morpheme boundary. The differences between suffixed and pseudo-suffixed words at the interval between the root and the suffix were not significant. This suggests that the processing of the suffix starts during the processing of the root and ends right before we start writing it.

This pattern of results suggests that the writing system activates the suffix to be written in parallel to the processing of the more peripheral parameters required for the production of the root, confirming the anticipatory character of Van Galen's (1991) handwriting production model. The suffix is activated during the production of the root. It starts at least before the initial syllable ends and continues until the morpheme boundary. It appears that numerically most of the processing is done at the letter preceding the morpheme boundary. This represents important progress in the understanding of the timing of handwriting production with respect to Kandel et al. (2008). Furthermore, the data also suggest that the syllable effect that Kandel and colleagues observed on inter-letter intervals (Kandel et al., 2006; Kandel et al., 2011) is stronger for bi-morphemic than for mono-morphemic words, but further research should be done to corroborate this point.

Experiment 1 showed that morphological structure regulates the timing of handwriting production at specific locations within a suffixed word. Experiment 2 examined whether this "morphological effect" is also observed in prefixed words. When we write, do we program the prefix and then the root?

## 3. Experiment 2

The objective of this second experiment was to determine whether morphological structure modulates the planning of prefixed words in handwriting. To examine this issue, we compared for example the production of the prefix ***in***- in prefixed words (e.g., ***in**édite* "novel, non edited") to the letter sequence *in* in pseudo-prefixed words (e.g., *inertie* "inertia"). As for suffixed words, we expected longer letter stroke and inter-letter interval durations in prefixed words than in pseudo-prefixed words. We also measured interval and letter durations at both the syllable and morpheme boundaries.

## 3.1. Method

### 3.1.1. Participants

Participants were the same as in Experiment 1.

### 3.1.2. Materials

We selected a total of 36 words (see Appendix B). Half of them were prefixed words (e.g., ***in**édite*). They contained various types of derivational prefixes (e.g., *an-*, *im-*, *in-*, *mal-*, *par-*, *post-*, *sub-*, *sur-*). We matched these prefixed words to pseudo-prefixed words that shared the same letters as the prefix in the same serial position (e.g., *inertie*). Thus, for the *inédite–inertie* pair, the syllable boundary was *i.nédite* for the prefixed word and the corresponding serial position (and syllable boundary) was *i.nertie* in the pseudo-prefixed word. For the morpheme boundary, we focused on the *né* sequence in ***in**édite* and the corresponding serial position (*ne*) in *inertie*. Please note that accent marks are generally not present when writing in upper-case letters in French. We explicitly asked the participants not to write accents whenever they could be present.

Prefixed and pseudo-prefixed words were matched for lexical and bigram frequency. According to the Lexique 2 French Data Base (New et al., 2001), the mean word frequency for prefixed words was 3.59 words per million, and the mean word frequency for pseudo-prefixed words was 4.64 words per million, $t(17)=.33$, $p=.74$. The mean bigram frequency at the syllable boundary was 643 for both prefixed and pseudo-prefixed words (Content & Radeau, 1988). The mean bigram frequency at the morpheme boundary for prefixed words was 365, and the mean bigram frequency at the same serial position for pseudo-prefixed words was 566, $t(17)=2.03$, $p=.06$ (Content & Radeau, 1988).

#### *3.1.3. Procedure and data analysis*

The procedure and data analysis correspond to those described for Experiment 1.

### *3.2. Results*

This section presents the results calculated from letter stroke durations and interval durations for prefixed and pseudo-prefixed words. The analyses were performed on both the syllable and morpheme boundaries. The results were also analysed using linear mixed effects models (Baayen et al., 2008; Bates, 2005).

#### *3.2.1. Letter stroke duration*

The stroke durations of the letter preceding the syllable boundary for prefixed and pseudo-prefixed words were 174 and 180 ms, respectively. At the morpheme boundary, they were 158 and 155 ms, respectively. The analyses did not yield any significant effect, $t<|1|$.

#### *3.2.2. Interval duration*

The interval durations at the syllable boundary for prefixed and pseudo-prefixed words were 146 and 147 ms, respectively. At the morpheme boundary they were 158 and 147 ms, respectively. The analyses did not yield any significant effect, $t<|1|$.

### *3.3. Discussion*

The goal of this experiment was to examine whether prefixed words are processed differently from pseudo-prefixed words in handwriting production. The lack of significant results for this experiment suggests that the writing system is not influenced by the presence of a prefix in a word. The timing of the movements needed to produce prefixed and pseudo-prefixed words appeared to be equivalent.

## 4. General discussion

The aim of this study was to examine whether the morphological structure of a word modulates the timing of motor programming in handwriting. The participants wrote affixed and pseudo-affixed words on a digitiser. We analysed movement time by measuring letter stroke and inter-letter interval durations. In Experiment 1, movement durations were longer for suffixed words than for pseudo-suffixed words at various locations. We observed these differences during the production of the root, both at the letter preceding the syllable boundary and the letter preceding the morpheme boundary. The inter-letter intervals were also longer in suffixed words than in pseudo-suffixed words. Note, however, that the differences were significant only at the syllable boundary. In Experiment 2, we selected prefixed words with various types of prefixes and compared their production to that of matched pseudo-prefixed words. The results were not conclusive since the analysis did not yield any significant differences for letter stroke durations or for inter-letter interval durations.

Globally, the results suggest that, at least for suffixed words, handwriting production does involve morpheme-sized processing units. The results on suffixes indicate that the activation of the information needed to write the suffix is spread in a cascaded fashion during the production of the root (see Fig. 1). Morpheme processing is carried out throughout the writing of the root and more precisely at the letter preceding the syllable boundary. Suffix processing continues to be active at the inter-letter interval located at the syllable boundary. The cognitive load seems to be particularly important at the letter preceding the morpheme boundary and then decreases at the inter-letter interval that separates the root from the suffix. The letter stroke and interval duration differences between suffixed and pseudo-suffixed words suggest that the motor system prepares the movement to produce the suffix well before having to write it. It starts during the production of the root and ends at the interval between the root and the suffix.

The results of the present study have further implications than those of previous research using on-line measures, because they show that the effects associated to morphological decomposition and processing are also observed in peripheral and late stages of writing. From a theoretical standpoint, the fact that the durations for suffixed words were higher than those for pseudo-suffixed words suggests that French speakers decompose suffixed words into root and suffix before starting to write them. The decomposition of suffixed words would be more time consuming than the direct access of a single unit, as in the case of pseudo-suffixed words. This result is in line with speech production research where latencies were affected by the morphological structure of words (e.g., Roelofs, 1996; Roelofs & Baayen, 2002; Zwitserlood et al., 2000). In fact, an interesting analogy can be established between our writing data and Koester and Schiller's (2008) conclusion that “morphemes are planning units in the production process and that language production proceeds incrementally from left to right” (p. 1623). This is also in agreement with Orliaguet and Boë (1993), who also found higher movement times and latencies for suffixed words than for mono-morphemic words in a handwriting experiment with inflectional morphology.

Our results also show that morphological programming is not fully completed when the motor response starts because the differences between suffixed and pseudo-suffixed words are present during the writing of the root. The morphological effects observed on letter durations and inter-letter intervals throughout the root question certain speech production and word recognition models claiming that morphologically complex words are represented and prepared as whole-word forms (e.g., Butterworth, 1983). We believe that our findings are more compatible with obligatory segmentation and dual-route models (e.g., Levelt, 1989; Roelofs, 1996; Taft & Forster, 1976). Of course, this issue goes beyond the objectives of our study. Further research that pits the predictions of the two models against each other should be carried out.

A second theoretical implication of our study is that the morphological effects were observed on movement times, which are late and peripheral measures as compared to the latency measures that are used in speech production and reading studies. Indeed, there are differences at the syllable boundary and even later, towards the end of the word, at the morpheme boundary. Our data demonstrate a functional relationship between central and peripheral processes, favouring a cascaded processing architecture, where operations related to motor execution are affected by central and linguistic factors (i.e., morphological decomposition). Recently, the notion of cascaded processing has been suggested to occur in handwriting for sound-to-spelling regularity effects (Delattre et al., 2006), syllabic effects (Álvarez et al., 2009; Kandel et al., 2011), and graphemic effects (Kandel & Spinelli, 2010). Delattre et al. (2006) give some reasonable arguments on why writing (in comparison to oral production) might be cascaded. Spelling is mastered later in life, it is less frequently used, it is more costly than speaking, and it takes longer to produce. We would add the function of the graphemic buffer, where the word's spelling has to be kept activated for a long time (in comparison with speech production) while successive letters are written. From this point of view, the letter stroke and interval duration differences between suffixed and pseudo-suffixed words that we found suggest that central – i.e., morphological – processing is operative when the response is being executed. It functions on-line and in parallel with the motor routines of handwriting.

Our data indicate that the morphological planning and segmentation of the word to be written are initiated before writing the suffix. It starts at the root (during the first syllable) and is carried over to affect the peripheral processes that occur later in the word. It is therefore likely that this processing could produce a sort of "re-activation" of the suffix. The processing of the suffix would be active at the syllable boundary (between *u* and *n* for *pru.n**eau***). There is a processing load between *u* and *n* because the handwriting system activates the information to produce the suffix (in *pin.ceau*, no suffix has to be programmed), and this processing is done in parallel with the calculation of the local parameters for the letter *u* (cf. Van Galen's, 1991 model). Later on in the word, at the boundary between the root and the suffix, there could be a sort of "re-activation" of the suffix, because the movement to produce it has to be programmed. The cognitive load also seems to be particularly important at the letter preceding the morpheme boundary (*n*) and then decreases numerically at the inter-letter interval that separates the root from the suffix (e.g., between *n* and *e*). Our results do not provide firm evidence for such an account, but future research is in progress to examine whether the suffix is kept active since the beginning of the word or whether it is re-activated at certain locations before the actual production of the suffix itself.

It should also be pointed out that the results were clear for suffixed words, but not for prefixed words. This could be due to the fact that the difference between prefixes and suffixes is not only positional. Suffixation is more frequent than prefixation (Cutler, Hawkins, & Gilligan, 1985; Greenberg, 1966), and French inflectional morphology only uses suffixes. Furthermore, this idea is in agreement with Baddecker et al.'s (1990) neuropsychological study, which found clearer effects of morphological structure for suffixed words than for prefixed words. Some results coming from the field of word recognition also support this difference. For instance, Colé, Beauvillain, and Segui (1989), who assumed sequential left-to-right processing in word recognition, proposed that suffixed words are accessed via the root, something that does not happen for prefixed words. In these kinds of word, the processing of the root does not precede that of the whole words form, so it is not possible to do an on-line exploitation of the information carried by the root in order to reach the correct lexical candidate. Roelofs (1996) also gives some arguments about the special status of prefixes in speech production. Because prefixes are metrically dependent (they cannot be a phonological word with at least a stressed syllable), they have to be adjoined to the phonological word corresponding to the base.

The results of Experiment 1 confirm the anticipatory motor programming conception of handwriting postulated by Van Galen's (1991) model. The data reinforce the idea that supplementary processing loads due to the programming of linguistic components produce duration increases. However, Van Galen's (1991) model and the more recent psycholinguistic model proposed by Kandel et al. (2011) do not consider morphemes as processing units in handwriting. Our study revealed that the processing of the suffix slows down movement within a letter-string by increasing the letter stroke and inter-letter interval durations situated at the syllable and morpheme boundaries. This rightward incremental pattern and the fact that the writing system seems to plan the forms of the successive morphemes in serial order are in line with the WEAVER model of word-form encoding in speech production (e.g., Levelt, Roelofs, & Meyer, 1999). This model provides a theoretical and computational account that conceives the word-form lexicon as a network of morpho-phonological nodes and labelled links. This proposal incorporates an independent morphological level and assumes seriality in planning the production of poly-morphemic words. The morphemes in a word are planned in serial order, such that non-initial morphemes cannot be programmed before initial ones (Roelofs, 1996).

The results for suffixed words indicate that handwriting production could also involve the activation of a morphemic processing level that stores derivational suffixes as processing units. The suffix would be an intermediate-grained sub-lexical unit between syllables and whole words that would provide information on the semantic aspects of the word. If morphemes are integrated into Kandel et al.'s (2011) model of handwriting production, a suffixed word such as *pruneau* would first be decomposed into root and suffix (*prun.eau*). Then, it would activate its syllabic components (*pru.n**eau***). It is unclear whether this activation will take place before or in parallel to syllable activation. At this level, syllables would be "unwrapped" into consonant and vowel constituents and serve as input to the allograph module, which would, in turn, decompose them into graphemes for allograph selection.

It is noteworthy that there is not always a direct mapping between syllables and morphemes. Morphemes in French or Spanish are often shorter than one syllable or they are formed by one syllable plus additional phonemes/letters. Clearly, this is a difficult problem that needs to be solved and that has been discussed in the field of word recognition (Álvarez, Carreiras, & Taft, 2001). Nonetheless, this kind of processing would be particularly important in French since a great majority of French words are morphologically complex (Rey-Debove, 1984) and given that it is a syllable-timed language. Weingarten et al. (2004) showed that in German typing, morpheme effects appear only when the syllable and morpheme boundaries coincide. In the words we selected for our experiments, the syllable and morpheme boundaries never coincided. This was done to avoid interpretation problems between syllable (Kandel et al., 2006) and morpheme effects. In addition, few French suffixed words share syllable and morpheme boundaries. Our study confirmed the morpheme effect, but revealed that this effect also appears when syllable and morpheme boundaries do not coincide. It is clear that the time course (serial vs. parallel) and the interface between syllabic and morphological levels are questions that need to be explored in the future in order to reach a better understanding of multi-level activations during handwriting production.

Finally, the results of this study are in line with neuropsychological data indicating that orthographic representations encode various levels of linguistic information (Caramazza & Miceli, 1990; McCloskey, Badecker, Goodman-Schulman, & Aliminosa, 1994) and in particular, information on morphological structure (Allen & Badecker, 2001; Baddecker et al., 1990). The findings of this study are also consistent with experimental research on handwriting production, which indicates that morphologically complex words lead to different processing mechanisms than mono-morphemic ones (Orliaguet & Boë, 1993). Future research should seek to clarify uncertainties that were raised by the present study, including: 1) whether our results can be generalized to other languages and the role of the characteristics of these languages on processing; 2) the concrete locus of the morphological effects in a future model of word writing; 3) whether morphological programming takes place in all kinds of words or depends on the word's linguistic properties, as suggested by models of word recognition (Caramazza et al., 1988); 4) the possible role and processing of inflectional morphology; and 5) as previously stated, how to integrate syllables and morphemes in a unique model, especially in those languages in which both units do not coincide.

## Appendix A

Word frequency (pm), global bigram frequency, bigram frequency at the syllable boundary and bigram frequency at the morpheme boundary for the suffixed and pseudo-suffixed words used in Experiment 1. NA = not available.

| Suffixed words | Word freq. (pm) | Global bigram Freq. | Bigram freq. (syll.) | Bigram freq. (morph.) | Pseudo-suffixed words | Word freq. (pm) | Global bigram Freq. | Bigram freq. (syll.) | Bigram freq. (morph.) |
|---|---|---|---|---|---|---|---|---|---|
| ARCEAU | 0.42 | 2.57 | 229 | 326 | CADEAU | 18.65 | 2.55 | 116 | 353 |
| BOTTINE | 0.35 | 2.9 | 563 | 1538 | SARDINE | 1.19 | 2.91 | 292 | 254 |
| BOULETTE | 1.35 | 2.93 | 428 | 1042 | OMELETTE | 2.97 | 2.72 | 532 | 1042 |
| CASQUETTE | 18.16 | 2.73 | 158 | 580 | CARPETTE | 1.19 | 2.67 | 67 | 253 |
| CENDRIER | 5.87 | 3.2 | 870 | 1046 | CHANTIER | 12.13 | 3.14 | 1154 | 1538 |
| COCOTIER | 0.48 | 2.95 | 218 | 1538 | ESCALIER | 69.39 | 2.73 | 479 | 595 |
| COUPELLE | 0.42 | NA | 171 | 253 | AISSELLE | 2.52 | 3 | 1045 | 780 |
| DRAPEAU | 15.16 | 2.51 | 172 | 253 | CORBEAU | 2.87 | 2.54 | 51 | 54 |
| ÉQUIPIER | 0.45 | 2.55 | 59 | 133 | SANGLIER | 3 | 2.91 | 271 | 595 |
| GAUFRETTE | 0.13 | 2.51 | 59 | 1100 | SQUELETTE | 8.52 | 2.58 | 532 | 1042 |
| JUPETTE | 0.71 | NA | 171 | 253 | BELETTE | 0.35 | 2.81 | 532 | 1042 |
| LAMELLE | 1.19 | 3.09 | 284 | 1108 | GAZELLE | 1.52 | 2.11 | 3 | 1 |
| PIÉCETTE | 0.35 | 2.49 | 236 | 326 | CREVETTE | 1.1 | 2.84 | 351 | 949 |
| PINCETTE | 0.13 | 2.77 | 842 | 326 | VIGNETTE | 0.65 | 2.72 | 294 | 504 |
| PLATEAU | 37.26 | 2.84 | 697 | 1243 | MOINEAU | 2.65 | 2.95 | 928 | 504 |
| POIVRIER | 0.16 | 3.07 | 318 | 1046 | ÉPERVIER | 1.61 | 2.69 | 112 | 203 |
| POUSSETTE | 1.16 | 3.01 | 1045 | 780 | BRAGUETTE | 2.9 | 2.7 | 375 | 580 |
| PRUNEAU | 0.74 | 2.57 | 133 | 504 | PINCEAU | 8.81 | 2.67 | 842 | 326 |
| RONDELLE | 1.32 | 2.94 | 870 | 353 | FLANELLE | 4.32 | 2.89 | 2448 | 504 |
| SALADIER | 1.23 | 2.83 | 116 | 254 | PEUPLIER | 2.48 | 2.92 | 171 | 595 |
| SUCETTE | 0.71 | 2.76 | 221 | 326 | VEDETTE | 9.32 | 2.56 | 26 | 353 |
| TÉTINE | 0.42 | 2.72 | 192 | 1538 | NARINE | 2.74 | 2.95 | 1016 | 1046 |
| TOMBEAU | 9.94 | 2.59 | 289 | 54 | CERNEAU | 0.06 | NA | 189 | 504 |
| Mean | 4.26 | 2.78 | 362 | 692 | | 6.99 | 2.75 | 514 | 592 |

## Appendix B

Word frequency (pm), global bigram frequency, bigram frequency at the syllable boundary and bigram frequency at the morpheme boundary for the prefixed and pseudo-prefixed words used in Experiment 2. NA = not available.

| Prefixed words | Word freq. (pm) | Global bigram Freq. | Bigram freq. (syll.) | Bigram freq. (morph.) | Pseudo-prefixed words | Word freq. (pm) | Global bigram Freq. | Bigram freq. (syll.) | Bigram freq. (morph.) |
|---|---|---|---|---|---|---|---|---|---|
| ANALPHABÉTE | 0.94 | 1.85 | 267 | 351 | ANIMALERIE | 0.03 | NA | 267 | 641 |
| IMMACULÉ | 1.55 | 2.46 | 312 | 684 | IMAGINER | 47.58 | 2.78 | 312 | 424 |
| IMMORAL | 0.94 | 2.7 | 312 | 684 | IMMOLER | 0.23 | 2.81 | 312 | 684 |
| INACTIF | 0.48 | 2.64 | 839 | 641 | INANITÉ | 1.26 | 2.92 | 839 | 641 |
| INACTIVER | 0.03 | NA | 839 | 641 | INANITION | 1.23 | 3.03 | 839 | 641 |
| INÉDITE | 1.94 | 2.6 | 839 | 129 | INERTIE | 0.23 | 2.64 | 839 | 504 |
| INÉGAL | 2.87 | 2.39 | 839 | 684 | INERTE | 8.45 | 2.91 | 839 | 504 |
| INEXACT | 0.97 | 2.18 | 839 | 504 | INEPTIE | 0.55 | 2.89 | 839 | 504 |
| INUTILE | 39.84 | 2.88 | 839 | 81 | INITIAL | 12.61 | 2.78 | 839 | 641 |
| MALADROIT | 5.29 | 2.83 | 479 | 480 | MALARIA | 0.71 | 2.61 | 479 | 480 |
| MALÉFICE | 0.61 | 2.57 | 479 | 74 | MALAXER | 0.19 | 2.61 | 479 | 480 |
| MALICE | 6.35 | 2.91 | 479 | 595 | MALIEN | 0.03 | 2.54 | 479 | 595 |
| MALOTRU | 0.45 | 2.59 | 479 | 528 | MALABAR | 0.45 | 2.45 | 479 | 480 |
| PARACHEVER | 0.77 | 2.96 | 1016 | 110 | PARASITER | 0.13 | 3.07 | 1016 | 110 |
| POSTOPÉRATOIRE | 0.06 | 2.8 | 618 | 245 | POSTILLONNEUR | 0.06 | NA | 618 | 1538 |
| SUBURBAIN | 0.19 | 2.41 | 92 | 35 | SUBITEMENT | 9.13 | 2.9 | 92 | 112 |
| SURAIGU | 0.9 | 2.6 | 1008 | 110 | SURANNÉ | 0.48 | 2.85 | 1008 | 110 |
| SURHOMME | 0.61 | 2.54 | 1008 | 1 | SUREAUX | 0.19 | NA | 1008 | 1100 |
| Mean | 3.59 | 2.58 | 643 | 365 | | 4.64 | 2.78 | 643 | 566 |

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