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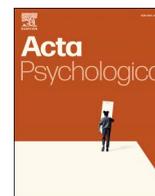
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Morphological processing in written word production is based on orthography rather than semantics

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ABSTRACT

Written word production is influenced by central and peripheral processes. Evidence suggests that the activation of morphological units in the lexicon influences the dynamics of handwriting. In this study, we designed two priming experiments to examine the representation level of morphological information in the lexicon during written word production in the French language. In both experiments, target words (e.g., *chanteur*, “singer”) were primed by a derived (e.g., *chanter*, “to sing”), a pseudo-derived (e.g., *chantier*, “work site”), or an unrelated (e.g., *baleine*, “whale”) prime. We used the pseudo-derivation condition to disentangle two distinct levels of representation: the sublexical (also known as morpho-orthographic) and the supralexical (morpho-semantic). In Experiment 1 (learning-recall task), we measured the writing latency and writing duration of the target words. In Experiment 2 (word pair copying task), we measured the inter-word duration and writing duration of the target words. We observed morphological priming effects in both experiments: The processing of a derived prime influenced target writing compared to an unrelated prime, but the effect was observed on latencies in Experiment 1 and on target writing duration in Experiment 2. We found similar patterns of priming in the derived and pseudo-derived conditions in both experiments. The findings revealed that morphemes are processed at the morpho-orthographic representation level in written word production. Morphemes serve as grouping units during handwriting, a process that operates independently of their meaning.

1. Introduction

The way morphologically complex words (i.e., composed of several morphemes, the smallest units of meaning in language) are stored and accessed in the lexicon is a major research topic in psycholinguistics (Feldman & Milin, 2018; Libben & Jarema, 2004; Marslen-Wilson et al., 1994; Taft & Forster, 1975). Murrell and Morton (1974) and Taft and Forster (1975) were the first to suggest the existence of an orthographic lexicon organized around morphological representations. Since then, four decades of publications on several languages and writing systems have investigated whether and under what conditions morphologically complex words are decomposed into smaller units during their written recognition (in French, Colé et al., 1989; Giraudo & Grainger, 2001; Longtin et al., 2003; in English, Beyersmann et al., 2012; Grainger & Beyersmann, 2021; Rastle et al., 2000; in Hebrew, Frost et al., 1997). By contrast, the morphological decomposition of words during their written production has been scarcely investigated. As language production does

not rely on exactly the same mechanisms as language recognition (Campbell, 1987; Hamilton & Coslett, 2007; Jones & Rawson, 2016; Moll & Landerl, 2009), it is crucial to examine whether and how morphological units influence the written production of morphologically complex words.

Word writing is a composite activity that involves two types of processes (Bonin et al., 2015; Lambert & Quémart, 2019; Purcell et al., 2011). The *central processes* (also known as spelling processes) refer to the cognitive mechanisms by which words are transcribed into written forms. Word spelling activation can occur through two pathways: the lexical route, whereby word spelling is activated directly from the orthographic lexicon, and the sublexical route, whereby word spelling is activated by mapping each phonological unit to the corresponding grapheme (Miceli & Costa, 2014; Rapp & Purcell, 2019; Tainturier & Rapp, 2001). The *peripheral processes* correspond to the kinematic aspects of writing: the speed of motor execution, the location and duration of writing pauses, and the pressure exerted on the pen or the keyboard.

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The activation of central and peripheral processes is not sequential: lexical and sublexical processing cascade into peripheral processing (Olive, 2014). Central processes are active during motor execution and modulate writing dynamics (Roux et al., 2013).

In written word production, letters are grouped into units called “chunks” (Kandel et al., 2009). This letter grouping reflects the influence of central processes on the dynamics of written production (Kandel et al., 2011). For instance, longer writing pauses have been observed between two letters located in two different linguistic units (i.e., between two syllables, e.g., in French, pa/rent, the slash marks the syllabic boundary) compared to letters located in a single linguistic unit (i.e., in the first syllable, e.g., in French, par/don) (Kandel et al., 2006). This slowing down is the consequence of the activation of the following syllable at the end of the first syllable (Álvarez et al., 2009; Kandel et al., 2006; Sausset et al., 2012).

Some studies have shown that morphemes also serve as grouping units in written word production. First, empirical observations have been made regarding patients with acquired writing disorders. Badecker et al. (1990) reported that following a stroke, patient DH produced fewer errors in word endings when they corresponded to suffixes rather than non-suffixed endings. Similarly, patient BH (Badecker, 1996) exhibited selective preservation of suffix spelling, while stems, although phonologically plausible, were misspelled. Conversely, Hamilton and Coslett (2007) reported that, following a brain injury, patient FP had selective difficulties in producing morphologically complex words (inflected or derived) in writing. To summarize, the nature of the errors made by these patients indicates that morpheme units can be selectively damaged or preserved in patients.

Other arguments come from studies measuring how the morphological structure of words influences temporal writing variables, such as writing latency, letter duration, and pause duration between letters in skilled writers (Afonso & Álvarez, 2019; Kandel et al., 2012; Quémart & Lambert, 2019). Writing latency is the delay between the presentation of a stimulus to a participant (whether presented visually or orally) and the moment when the tip of the pencil touches paper or the first keystroke occurs. In a copying task in French, suffixed words were initiated faster than morphologically simple words (Quémart & Lambert, 2019). This result was interpreted as the consequence of the faster activation of orthographic representation for suffixed words than for simple words, probably due to the presence of a shorter and more frequent morpheme, which is easier to access in the lexicon than the whole word form. This interpretation has been corroborated by the results of Afonso and Álvarez (2019). In their study, adult writing latency was influenced by the frequency of each morpheme. In Spanish, compound words composed of a first or second highly frequent morpheme (e.g., *Nochebuena*, “Christmas Eve”) are initiated faster than compound words composed of two low frequency morphemes (e.g., *tragaperras*, “slots machine”). However, the issue is not entirely clear-cut: Bertram et al. (2015), using a design quite similar to that of Afonso and Álvarez (2019), did not observe any effect of morpheme frequency on adult typing latency.

Morphological units also influence the writing dynamics of words. In a word-copying task, the writing duration of the letter preceding the morphemic boundary for suffixed words (e.g., vol/eur, the slash marks the morphemic boundary) was longer than the writing duration of the same letter at the same position but belonging to a morphologically simple word (e.g., soleil) (Quémart & Lambert, 2019). The production of compound words in Spanish (Afonso & Álvarez, 2019) and Finnish (Bertram et al., 2015) also involves slower writing speed at the morphemic boundary, which supports the notion that morphological information influences written word production.

These findings shed some light on the central processes involved in writing morphologically complex words. The findings indicate that such words are decomposed into their roots and affixes at some stage in the processing and that the morphological structure of words influences writing latency and writing speed.

In an attempt to model morphological processing in written word production, Quémart and Lambert (2019) proposed adapting Kandel et al.'s (2011) model of handwriting production by introducing a level of morphological representation. According to Quémart and Lambert (2019), the lexical level is based on morphology, and word spelling is recovered through the morphological constituents of words rather than through the activation of the whole word. The addition of a morphological processing level in the architecture of a written production model constituted the first step toward a better understanding of the processes involved in word writing. However, this proposal did not provide any information on the representation level of morphological information in the lexicon. Morpheme units have, indeed, been shown to be processed at two levels in the reading lexicon (e.g., Diependaele et al., 2005, 2009). The first level is *morpho-orthographic*. This sublexical level codes purely formal (i.e., orthographic) information on morphemes (i.e., all sequences of graphemes and phonemes that constitute morphemes in a language) and is accessed prior to whole-word representations (e.g., Taft, 1994; Taft & Forster, 1975). At this level, the processing of morpheme units in words is independent of their meaning. The second level of processing is *morpho-semantic*. This supralexical level codes morphemes' lexical and syntactic properties and acts as an intermediate level between whole-word representations and the semantic system. Access to this level is based on lexically stored information (e.g., Giraudo & Grainger, 2000; Marslen-Wilson et al., 1994).

Support for the existence of these two levels of representation has been provided in the field of word recognition, mainly through the priming paradigm. The recognition of morphologically complex words consists of the successive activation of these two processing levels (Diependaele et al., 2005, 2009; Järvikivi & Pykkönen, 2011; Meunier & Longtin, 2007; Quémart et al., 2011; Rastle et al., 2000). The existence of these two processing levels has been supported by experiments involving the manipulation of prime duration. When primes are presented very briefly (<60 ms), masked priming effects show that letter sequences are first grouped into morpheme-sized chunks that are accessed independently of their meaning. At the morpho-orthographic processing level, words are decomposed into smaller units even when they are not truly morphologically complex (e.g., “corner” decomposed into “corn” and “er”, although “corner” is not morphologically complex). In terms of priming effects, both morphologically complex (e.g., “competition”) and pseudo-derived (e.g., “competence”) word primes facilitate target (e.g., “compete”) recognition relative to unrelated primes (Beyersmann et al., 2011; Beyersmann et al., 2014; Longtin et al., 2003; McCormick et al., 2008; Rastle et al., 2004; Rastle & Davis, 2008). A different pattern of priming has been observed when primes can be processed explicitly (i.e., when they are presented for >200 ms): Only truly morphologically complex word primes facilitate target recognition relative to unrelated primes (“compete” is primed by “competition” but not by “competence”). At this morpho-semantic level, morphemic representations are activated after whole-word orthographic representations (Marslen-Wilson et al., 1994; Meunier & Segui, 2002), and only words that belong to the same morphological family are connected. In summary, the morpho-orthographic processing level is indexed by pseudo-derivation priming effects (Rastle et al., 2000).

1.1. The present study

The issue of the representation level of morphological information in written word production has never been investigated. Here, we designed two studies to investigate this issue using the priming paradigm. We examined the extent to which a prime influences writing latencies and writing durations for the same target word according to the type of relationship between the two words. In both studies, the targets to write were morphologically complex words (i.e., derived words, e.g., *chanteur*, “singer”), and each was preceded by three different primes: a derived word (e.g., *chanter*, “to sing”), a pseudo-derived word (e.g., *chantier*, “worksite”), and an unrelated word (e.g., *baleine*, “whale”). By

comparing the priming effects of derived and pseudo-derived words, we sought to determine whether morphological units are processed at the morpho-orthographic or the morpho-semantic representation level. Comparing writing latencies and writing durations for the same targets allowed us to obtain strict experimental control over the peripheral processes involved in word production, an essential control when measuring writing dynamics.

The two experiments used different tasks. To ensure that participants would write the right target word (e.g., *chanteur*, “singer”), we asked them to memorize prime-target pairs before the writing task (Experiment 1). For example, the participants had to learn that when presented with the word *chanter* (“to sing”), they should write *chanteur* (“singer”), or that when presented with the word *baleine* (“whale”), they should write the word *chanteur* (“singer”). In Experiment 2, we removed the memory constraints that were part of the task in Experiment 1 by asking the participants to copy pairs of words, the first word being the prime (e.g., *chanter*, “singer”) and the second word being the target (e.g., *chanteur*, “to sing”).

Both experiments were conducted in French. With 80 % of words considered morphologically complex (Rey-Debove, 1984), French can be considered a morphologically rich language. Words can be constructed in three ways: by inflection (to express grammatical categories, e.g., *maison/s*, “house/s”), by derivation (to create a new word by adding an affix to a root, e.g., *maison/ette*, “little house”), and by composition (to create a new word by joining together two roots, e.g., *porte-manteau*, “coat rack”). In our study, we focused on the mechanisms involved in the writing of derived words. In the case of French derivation, affixes can be placed either at the beginning of a word (a prefix) or at the end of a word (a suffix). Morphologically derived words constitute approximately 60 % of the words in the French language (Mailhot et al., 2020). In the two experiments presented here, we only used words derived by suffixation.

Our first aim was to confirm that the presence of morpheme units influences the dynamics of written derived word production. To date, only a few studies have shown the influence of morphemes on the production of written words. Here, we aimed to generalize these findings using a priming-based protocol. We assumed that target words would be decomposed into morpheme units during the writing process (Afonso & Álvarez, 2019; Kandel et al., 2012; Quémart & Lambert, 2019) and that such decomposition would be influenced by the preceding prime. The presentation of a derived word prime should pre-activate the morpheme units in the lexicon and thus facilitate spelling recovery to produce the target compared to an unrelated prime word. Therefore, we assumed that target words would be initiated earlier (latency measure) and written slower (writing duration measure) when preceded by a derived word prime (e.g., *chanteur* preceded by *chanter*) than when preceded by an unrelated word prime (e.g., *chanteur* preceded by *baleine*), as already evidenced in other studies using other paradigms (Afonso & Álvarez, 2019; Kandel et al., 2012; Quémart & Lambert, 2019).

The second aim concerned the representation level of morphological information in written word production. If morphological processing is based on the activation of morpho-orthographic representations, priming effects should be observed when the prime is a derived word (e.g., *chanter* – *chanteur*) or a pseudo-derived word (e.g., *chantier* – *chanteur*). At the same time, if morphological processing relies on the activation of a morpho-semantic representation level, priming effects should only be observed when primes are morphologically related to targets (i.e., derived words, e.g., *chanter* – *chanteur*).

2. Experiment 1

2.1. Methods

2.1.1. Participants

Forty-seven undergraduate students from the University of Poitiers ($M = 21.3$ years, $SD = 2.84$) participated in the study. They were all

enrolled in Psychology courses and received course credits for their participation. The sample included 34 women (72.3 %) and 13 men. All participants were native speakers of French and reported normal or corrected-to-normal vision. None had been diagnosed with a language disorder. The participants signed a consent form before the experiment. The experiment was declared to the General Data Protection Regulation of the University of Poitiers and was approved by the Research Ethics Committee of the University of Poitiers.

2.1.2. Materials

Twenty target words and 60 prime words were selected as experimental stimuli. The full list of items is provided in Appendix A. Each target was a suffixed word (e.g., *chanteur*, “singer”) and was primed by three words according to three different relationships (derived, pseudo-derived, and unrelated). In the derived condition, the primes were morphologically related to the targets. These primes shared the same root as the target words but had a different derivational suffix (e.g., *chanter*, “to sing”). In the pseudo-derived condition, the primes shared the same beginning letters as the target and ended with a pseudo-suffix (i.e., a sequence of letters that corresponds to a suffix but does not serve as a suffix here) but were neither morphologically nor semantically related to the targets (e.g., *chantier*, “worksite”, in which *ier* is a pseudo-suffix). Finally, in the unrelated condition, the primes were morphologically simple words that shared neither a morphological, an orthographic, nor a semantic relationship with the target (e.g., *baleine*, “whale”). The stimuli characteristics are presented in Table 1. The three priming conditions were matched in terms of lexical frequency, $F < 1$ (from the French database Lexique; New et al., 2004), the number of letters, $F < 1$, and the number of syllables, $F < 1$. The number of shared letters between the targets and the primes in the two related conditions (i.e., derived and pseudo-derived) was not statistically different (Wilcoxon $W = 230$, $p = .384$) and was greater than in the unrelated condition (derived vs. unrelated, $W = 399.5$, $p < .001$; pseudo-derived vs. unrelated, $W = 399.5$, $p < .001$).

The 60 prime-target words were divided into 20 blocks of three trials. Each block consisted of three pairs of words, each pair corresponding to a priming condition (derived, pseudo-derived, or unrelated). The three targets presented in each block were different: a given target never appeared twice in the same block.

2.1.3. Apparatus

Stimulus presentation and the recording of the written response were controlled by the Eye and Pen software (Alamargot et al., 2006). The experiment was run on a Dell Latitude E6500 laptop computer. A Wacom Intuos 3 graphics tablet connected to the laptop and a Wacom Inking pen were used to record the participants' responses. A sheet of A5 paper marked with two columns of five rows was attached to the tablet and was changed between the two trials each time it was full.

Table 1

Stimulus properties across priming conditions (standard deviations shown in parentheses).

Priming condition	Example	Frequency	Number of letters	Number of syllables	Number of shared letters with the target
Target words	<i>Chanteur</i> (“singer”)	10.03 (35.07)	8.00 (1.26)	2.6 (0.75)	–
Prime words					
Derived	<i>Chanter</i> (“to sing”)	13.39 (25.80)	7.05 (1.00)	2.2 (0.41)	4.70 (0.92)
Pseudo-derived	<i>Chantier</i> (“worksite”)	5.26 (7.02)	7.40 (0.99)	2.25 (0.44)	4.40 (0.68)
Unrelated	<i>Baleine</i> (“whale”)	4.26 (4.27)	7.60 (0.99)	2.3 (0.47)	0.65 (0.81)

Note. Frequency is provided in occurrences per million (New et al., 2004).

2.1.4. Procedure

The participants were tested individually at the University. The participants were informed that they would first have to learn pairs of prime-target words in blocks of three. Then, they would have to recall the second word of each pair when the first word appeared on the computer screen. The experiment was divided into learning and recall phases, as shown in Fig. 1.

2.1.4.1. Learning phase. The participants had to learn pairs of words displayed on a computer screen. To reduce the effect of working memory overload, the participants learned pairs in blocks of three, which comprised one pair for each priming condition. The three pairs were presented in a vertical list on the screen (Calibri font, size 33), and the participants could spend as much time as needed to learn the pairs (the time spent learning word pairs was not registered). The presentation order of the 20 blocks was randomized among the participants.

2.1.4.2. Recall phase. At the end of each learning phase, the participants were prompted to write the memorized targets in their usual writing style. To determine which target to write, the three primes were presented successively on the screen according to the following sequence: First, a fixation cross was presented at the center of the screen. Second, the experimenter displayed the prime by pressing the “Enter” key on the keyboard. Third, the participants wrote, as quickly and accurately as possible, the corresponding target on a piece of lined paper (one line per word to be written). The stimulus disappeared from the screen as soon as the participants started writing to prevent them from looking back at the primed word. Fourth, when they had finished writing, the participants used the pen to click on a dedicated area on the tablet to trigger the next trial. Once the participants had reported the three targets associated with the three primes, they moved on to learning the next three pairs. Before the start of the experiment, the participants practised with two preparatory blocks of prime-target pairs to ensure that they understood the task. The presentation order of the blocks and the pairs in each block was randomized.

2.2. Results

For each trial, we measured accuracy in recalling (percentage of words recalled correctly) and spelling (percentage of target words spelled correctly), writing latency (i.e., the time in ms between the presentation of the stimulus and a participant's start of writing), and writing duration (i.e., the time in ms between the pencil's first touch on

the tablet and the last raising of the pencil). The means and standard deviations by group and priming condition for these four variables are reported in Table 2.

Analyses of writing latency and writing duration were conducted using correct responses (i.e., words spelled correctly and without erasures, corresponding to 87.98 % of the dataset). Outlier trimming was conducted on response times. For the writing latency analysis, response times below 100 ms were considered unrelated to word processing (e.g., recording failure, premature writing before the prime was displayed) and were removed (0.68 %). Response times below or above three standard deviations from the mean were then excluded (2.58 %). For the writing duration analysis, response times below or above three standard deviations from the mean were also removed from the analysis (0.97 %). For both dependent variables, the data were logarithmically transformed to meet normality assumptions. Linear mixed-model analyses were then carried out using the lme4 package (Bates et al., 2015) in R (R Development Core Team, 2012). The models included Priming condition (derived, pseudo-derived, unrelated) as fixed effect and Participants and Items as random effects (Baayen et al., 2008).

2.2.1. Writing latency

The main effect of the priming condition on writing latency was significant, $F(2,2352) = 27.06, p < .001$. Planned comparisons were conducted to examine priming effects according to the priming condition. Writing latencies were longer for targets primed by unrelated primes than derived primes, $t(2353) = 6.29, p < .001$, and pseudo-derived primes, $t(2353) = 6.55, p < .001$. However, the influence of the derived and pseudo-derived primes on target writing latencies was the same ($t < 1$).

Table 2

Mean percentages of correct recalls and spellings, writing latencies, and writing durations of the targets in Experiment 1 (standard deviations are shown in parentheses).

Priming condition	Percentage of correct recall	Percentage of correct spelling	Writing latency (ms)	Writing duration (ms)
Derived	95.85 (6.45)	92.34 (8.71)	1301 (310)	3184 (546)
Pseudo-derived	95.53 (5.83)	92.13 (8.89)	1316 (312)	3201 (519)
Unrelated	89.26 (12.20)	86.28 (13.25)	1497 (406)	3189 (541)

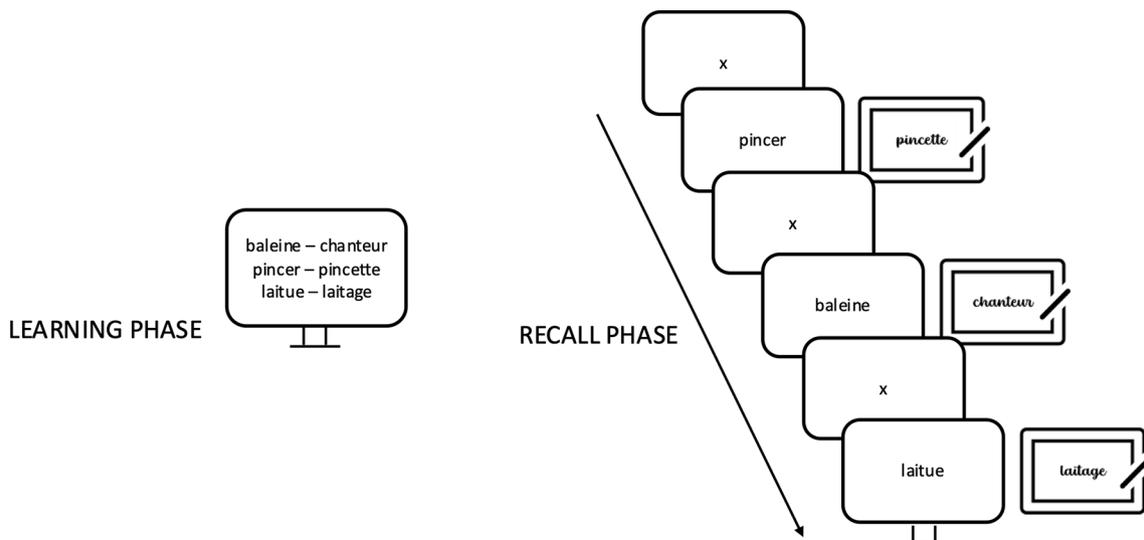


Fig. 1. Illustration of the procedure of Experiment 1.

2.2.2. Writing duration

The priming condition did not significantly influence word writing duration ($F < 1$).

2.3. Discussion

The aim of this experiment was to investigate the representation level of morphological information in written word production. We used a priming paradigm whereby participants were asked to write down target words for primes presented on a computer screen. Each target was previously coupled with a derived prime, a pseudo-derived prime, and an unrelated prime in the learning phase.

The results showed that a target was initiated faster after being primed by a word with a derivation or a pseudo-derivation relationship compared to an unrelated prime. However, there was no difference in writing latency when the targets were primed by derived or pseudo-derived words. Regarding writing duration, there was no difference between the three priming conditions: the presentation of a derived or a pseudo-derived prime did not modulate the writing duration of morphologically complex words compared to an unrelated prime. In general, priming effects were observed for latency only and were significant when the prime and the target shared morpheme units, whether in a genuine morphological relationship (e.g., *chanter-chanteur*) or in a pseudo-derivation relationship (e.g., *chantier-chanteur*).

These results can be interpreted in reference to the morphological processing model proposed by Diependaele et al. (2005, 2009, see also Grainger & Ziegler, 2011). According to this model, the processing of morphological units occurs at two distinct levels: morpho-orthographic and morpho-semantic. The similar facilitation effect observed in the derivation and pseudo-derivation conditions likely reflects an activation of units at the morpho-orthographic level – that is, at the sub-lexical level. This kind of processing consists in activating the morpheme units embedded in prime words independently of their meaning (e.g., “chant” in “chanter” and “chant” in “chantier”); such activation facilitates subsequent access to the target word to write (e.g., “chanter”).

These results also shed light on the processes involved in word handwriting. Several processes are implicated in word production and can have a joint influence on writing latencies (e.g., Bonin et al., 2015; Quémart & Lambert, 2019). In the case of our study, at least three different processes can be identified. The first two processes are related to the central activation of words. The first process is the retrieval of the target from working memory. Our paradigm involved the retention of sets of three word pairs in working memory and the retrieval of the correct target when the associated prime was presented. The second process is the retrieval of the corresponding graphemes from the orthographic lexicon. All the graphemes that constitute a word must be activated and sent to the orthographic working memory while waiting to be produced (Purcell et al., 2011). Finally, the third process is peripheral and corresponds to the planning and execution of handwriting gestures (Ellis, 1982; van Galen, 1991).

In the time course of handwriting, when does this priming effect on latencies occur? Given that the percentage of correct recalls was high, we consider the likeliest hypothesis to be facilitation at the level of word spelling retrieval from the lexicon. However, we cannot completely rule out the possibility that priming effects may reflect faster word retrieval from working memory, especially because priming effects were significant for latencies but not for writing durations. To eliminate this possibility, we conducted another experiment, in which new participants were asked to perform a copying task of word pairs (using the same primes and targets as in Experiment 1). We chose this task because it was supposed to free participants from working memory constraints. Moreover, by asking the participants to copy both the prime and target words, we ensured a deeper processing of the prime than just reading it.

3. Experiment 2

3.1. Methods

3.1.1. Participants

A new sample of 45 undergraduate students from the University of Poitiers ($M = 19.88$ years, $SD = 0.89$) participated in the study. As in Experiment 1, they were all enrolled in Psychology courses and received course credits for their participation. The sample included 41 women (91.11 %) and five men. All participants were native French speakers and reported normal or corrected-to-normal vision. None reported having a language disorder. The participants signed a consent form before the experiment. The experiment was declared to the General Data Protection Regulation of the University of Poitiers and was approved by the Research Ethics Committee of the University of Poitiers.

3.1.2. Materials

The materials were the same as in Experiment 1.

3.1.3. Apparatus

The apparatus was the same as in Experiment 1.

3.1.4. Procedure

The participants were tested at the University of Poitiers. They were asked to perform a word copying task in the following sequence: First, the participants were asked to look at the fixation cross on the screen and position the pencil at the spot where they will begin writing. Second, the experimenter displayed a word pair (Calibri font, size 33) by pressing the “enter” key on the keyboard. Third, the participants were asked to copy, as quickly and accurately as possible, the two words of the pair on a dedicated sheet in their usual writing style. The stimulus disappeared from the screen as soon as the participants started writing to prevent them from looking back at the words. Fourth, after writing the words, the participants pressed a dedicated area on the digitizer. This triggered the appearance of the fixation cross. The presentation order of the 60 word pairs was randomized among the participants.

3.2. Results

The mean percentages of correct recalls and spellings, mean inter-word writing intervals (i.e., the duration of the pen lift between the end of prime-word writing and the beginning of target-word writing), and target writing durations are reported in Table 3. Analyses of inter-word writing intervals and writing duration were conducted using correct responses (i.e., word pairs spelled correctly and without erasures, corresponding to 94.66 % of the dataset). One participant was excluded because of problems with data recording during the test. The outlier trimming procedure was similar to that of Experiment 1. The data below and above three standard deviations from the mean were considered outliers and were removed from the analysis (i.e., 0.92 % and 0.88 % for inter-word intervals and writing durations, respectively). Inter-word writing intervals and target writing durations were then logarithmically transformed to meet normality assumptions. Linear mixed-model analyses were carried out on correct responses for both dependent

Table 3

Mean percentages of correct recalls and spellings, inter-word writing interval duration, and writing duration of the targets in Experiment 2 (standard deviations are shown in parentheses).

Priming condition	Percentage of correct recall	Percentage of correct spelling	Inter-word writing interval (ms)	Writing duration (ms)
Derived	99.04 (9.78)	95.18 (21.43)	445 (111)	3369 (599)
Pseudo-derived	98.81 (10.86)	95.68 (20.32)	447 (109)	3372 (604)
Unrelated	98.92 (10.35)	96.70 (17.87)	457 (119)	3331 (623)

variables using the lme4 package (Bates et al., 2015) in R (R Development Core Team, 2012). As in Experiment 1, the models included Priming condition (derived, pseudo-derived, unrelated) as fixed effect and Participants and Items as random effects (Baayen et al., 2008).

3.2.1. Inter-word writing interval

The main effect of the priming condition on inter-word writing intervals did not reach significance ($F < 1$).

3.2.2. Writing duration

We found a significant effect of the priming condition on target writing duration, $F(2, 2430) = 4.43, p = .012$. Planned comparisons indicated that writing durations were faster in the unrelated condition than in the derived condition, $t(2430) = 2.78, p = .005$, and in the pseudo-derived condition, $t(2430) = 2.29, p = .022$. However, writing durations were not different in the derived and pseudo-derived conditions ($t < 1$).

3.3. Discussion

In Experiment 2, we wanted to examine the influence and the representation level of morphological units in the written production of morphologically complex words by means of a word-copying task coupled with the priming paradigm. The participants were asked to copy pairs of words (the same as in Experiment 1) presented on a computer screen. The inter-word interval and the target writing duration were registered.

The results can be summarized as follows: For the inter-word writing interval, the effect of the priming condition was not significant: the relationship between the two words of the pair did not significantly influence the time needed to begin writing the target word. By contrast, the priming condition did influence target writing duration: words were produced more slowly when primed by a related word (regardless of whether this was a derivation or a pseudo-derivation relationship) compared to being primed by an unrelated word.

First, these results shed light on the representation level of morpheme units in the production lexicon. Similar priming effects were observed for targets primed by a derived or a pseudo-derived word. Therefore, the same type of mechanism is probably at work in both conditions. When writing, targets seem to be first decomposed into morphemes, and this decomposition operates independently of the derived or pseudo-derived status of the primes. In accordance with what was observed in Experiment 1, morpheme units seem to be represented at the morpho-orthographic level in the orthographic lexicon.

Second, this result clarifies the underlying process involved in priming effects. Experiment 1 involved a cognitive load because the participants were asked to maintain three pairs of words in working memory at each trial. Consequently, the hypothesis of a purely mnemonic effect could not be directly ruled out. In addition, priming effects were observed for writing latencies only (i.e., a variable particularly sensitive to mnemonic processing). These two points prevented us from deciding between two possible interpretations of the priming effects: word retrieval from working memory and word spelling retrieval. Experiment 2 did not involve maintaining three pairs of words in working memory and yet priming effects were still observed on writing duration (i.e., no effect on writing latency), which strongly limits interpretation in terms of the memory-retention effect. These results suggest that the central processes activated during prime writing remain active during the writing of the target. Therefore, priming effects observed in Experiment 2 can be attributed to the activation of morpheme-sized units during handwriting rather than memory retrieval.

Third, inhibitory priming effects were observed: the writing duration of a word increased when the preceding word was related to the word being written compared to when the preceding word was unrelated. By contrast, facilitating priming effects were observed in Experiment 1.

This result will be further discussed in the General Discussion.

4. General discussion

In a recent study, morphologically derived words were shown to constitute approximately 60 % of the words in the French language (Mailhot et al., 2020). Therefore, understanding how such words are processed in writing is critical to the development of models of written production (Quémart & Lambert, 2019). In this section, we discuss our two aforementioned experiments designed to examine how writers produce morphologically complex words in writing.

In line with the few studies published on this issue so far (Afonso & Álvarez, 2019; Bertram et al., 2015; Kandel et al., 2012; Quémart & Lambert, 2019), we aimed at improving our understanding of morpheme processing in written production by examining the representation level of morphological information in writing. To achieve our aim, we used the priming paradigm, which had never been used before to investigate this issue. In the two experiments, the participants were asked to write a morphologically complex word (e.g., *chanteur*) primed by a derived word (e.g., *chanter*), a pseudo-derived word (e.g., *chantier*), or an unrelated word (e.g., *baleine*). In Experiment 1, the participants had to memorize the prime-target associations, which means that the visual presentation of a prime elicited the writing of the appropriate target. In Experiment 2, we freed the participants from the working memory load and asked them to copy the prime-target pairs. In both experiments, we measured the time needed to begin writing the target word (writing latency in Experiment 1, inter-word interval in Experiment 2) and the writing duration of the same morphologically complex word. These two variables were compared as a function of the priming relationship (derivation, pseudo-derivation, or unrelated).

4.1. Morphological priming in writing

In both experiments, the writing of the same morphologically complex word was influenced by the presentation of a derived prime word rather than an unrelated prime. It should be noted here that morphological priming effects are not limited to an orthographic overlap effect between primes and targets. Morphological overlap between primes and targets indeed also implies an orthographic overlap. For this reason, patterns of priming for morphologically related words are generally compared to priming effects for words that share the same letters but without morphological relationship. Two types of control conditions are generally used: a pseudo-derivation condition and/or an orthographic control condition. Unlike the pseudo-derivation condition (which we used in this study), the orthographic control condition involves word pairs that do not end in a suffix ending. We were not able to include this control condition in the two experiments presented here, due to a lack of such words in the French language: it was not possible to select enough triplets that shared a morphological, pseudo-derivation or orthographic control relationship with the same target.

To ensure that the priming effects were not due to orthographic overlap only, we performed an additional statistical analysis. We investigated whether, at equivalent (pseudo) morphological overlap, the number of letters shared between the prime and the target could explain the priming effects. We examined the effect of the number of shared letters (between 3 and 6 letters in the two related conditions) on writing latency and writing durations. If priming effects are the only consequence of orthographic overlap, then they should be higher when primes and targets overlap across six letters rather than three letters. The results showed that in Experiment 1, orthographic overlap had no effect on writing latency ($F < 1$) or writing duration, $F(1, 1597) = 2.841, p = .092$. Similarly, in Experiment 2, the condition had no effect on writing latency ($F < 1$) or writing duration, $F(1, 1595) = 1.085, p = .298$. The results indicate that, for equivalent (pseudo)morphological overlap, high orthographic overlap does not facilitate target writing (in terms of latencies or durations) compared to low orthographic overlap. This

indicates that our results cannot be explained by a simple orthographic overlap effect, which constitutes an additional argument in favour of morphological processing of words during handwritten production.

The first implication of this result that we wish to highlight is that it is possible to modulate the writing speed of a given word according to the word that precedes it. In the literature, this priming effect has also been called the “delayed effect.” In a study of narrative text production by students aged 10–15 years, [Maggio et al. \(2012\)](#) showed that a word's writing dynamics are influenced by the number of letters and by the neighborhood frequency of the word that precedes it. Our results are consistent with those of [Maggio et al. \(2012\)](#), indicating that the writing of a word is influenced by the characteristics of the word that precedes it. The orthographic processes related to the previous word are still active during the writing of the next word, which is consistent with the idea that central processes cascade into the peripheral processes of writing ([Olive, 2014](#); [Roux et al., 2013](#)).

The second implication of morphological priming that we wish to highlight is that the morpheme is the processing unit that remains active during motor execution. It is likely that the same morphological unit is activated during the processing of the prime and the target and that this shared unit influences the writing of the target. The influence of morphemes on word writing has already been demonstrated through an isolated word-copying task ([Afonso & Álvarez, 2019](#); [Bertram et al., 2015](#); [Kandel et al., 2012](#); [Quémart & Lambert, 2019](#)). In both experiments, the morphological relationship between the prime and the target influenced the target writing dynamics, compared to an unrelated prime-target pair. These morphological priming effects confirm that a word's morphological structure influences the dynamics of writing production and that the morpheme constitutes a processing unit in handwriting.

4.2. Representation level of morphological information

To further understand morphological processing in written production, we now turn to the issue of the representation level of morphological information. For the last 20 years, this issue has strongly animated the debates in the field of written word recognition ([Diependaele et al., 2009](#); [Järvikivi & Pyykkönen, 2011](#); [Rastle et al., 2000](#)), but it has not been studied in the field of written word production. In visual word recognition, the priming paradigm has shown that morphemes are represented at two distinct levels: the sub-lexical level (also known as “morpho-orthographic”), which encodes morphemes as orthographic units without considering their meaning, and the supra-lexical level (also known as “morpho-semantic”), which connects morphemes to words from the same morphological family ([Diependaele et al., 2005, 2009](#); [Rastle et al., 2000](#)). During word recognition, these two processing levels are activated successively (but see [Feldman et al., 2009](#) for alternative results). At the start of processing, morpheme units are extracted independently of their meaning ([Rastle et al., 2004](#)). Thereafter, only the extracted morphemes that are semantically connected to the morphologically complex word remain active ([Marslen-Wilson et al., 1994](#); [Meunier & Longtin, 2007](#); [Meunier & Segui, 2002](#); [Rastle et al., 2000](#)). Therefore, the priming potential of pseudo-derived words can only be observed in the early stages of processing, when the prime's presentation time is so short that it cannot be processed intentionally by the participants (i.e., masked priming).

In the two experiments reported in this article, the magnitude of the priming effects was the same, regardless of whether the prime was derived or pseudo-derived from the target. During prime writing, the activation of an embedded morpheme (a root: “chant” in “chanter”; or a pseudo-root: “chant” in “chantier”) influences the written production of the target, regardless of whether the target is semantically related to the prime or not. This finding supports the involvement of a morpho-orthographic representation level during written word production. Morphologically complex words are broken down into “morpheme-like” orthographic units which influences subsequent target writing,

independently of their meaning. This result indicates that morphological processing in written word production is based on orthography rather than semantics.

This finding may seem surprising when compared to written word recognition, as primes could be processed intentionally and without time limit in both experiments. As explained above, morpho-orthographic priming effects in relation to visual word recognition could only be observed when the priming could not be processed intentionally. At the same time, this result is fully consistent with some results reported for spoken word production. [Roelofs and Baayen \(2002\)](#) investigated whether the semantic relationship between a whole word and its constituent morphemes (semantic transparency) influenced the amount of priming. By comparing semantically transparent words (similar to the derived words in our experiments) and opaque words (similar to the pseudo-derived words in our experiments), they showed that morphemes' beneficial effect on naming latencies was the same for both types of words. Comparable effects of transparent and opaque compound words were also observed in a picture-word interference task ([Dohmes et al., 2004](#)). Therefore, it appears that in the domain of word production, written or spoken, morphological processing relies on the activation of morpheme-like units independently of their meaning.

4.3. Task effect on morphological priming

Although both experiments revealed morpho-orthographic priming effects, the results observed may seem inconsistent. When the participants had to reactivate the target word from memory (Experiment 1), the priming effects resulted in shorter target writing latencies. By contrast, when the participants were asked to copy prime-target pairs (Experiment 2), the writing duration of the targets was longer when the latter were preceded by a related prime compared to an unrelated prime. In summary, the localization and the direction of the priming effect were not the same in the two experiments.

Is it possible to reconcile these apparently conflicting results? Regarding effect localization, the two tasks probably involve distinct processes. The cognitive demands inherent in the task have already been shown to modulate the dynamics of word writing. In a study conducted in the French language, [Bonin et al. \(2015\)](#) showed that written naming relies more on the lexical pathway of word writing than do spelling to dictation and copying tasks. In addition, cascading processes have also been shown to be flexible as a function of task demands: in a word-copying task, writers may process syllables in words prior to or during graphomotor execution, depending on the task's graphomotor constraints ([Sausset et al., 2012](#)). In general, the task modulates the processes involved in writing as well as the time course of word production.

In Experiment 1, the task that demanded the most lexical processing, the retrieval of the orthographic form from memory seemed to occur before writing (i.e., during writing latency). During this period, the participants had to retrieve the word from memory and prepare for graphomotor execution (e.g., retrieving allographic codes). It is, therefore, possible that the effects can be explained by memory load. In Experiment 2 (the copying task), writing latency (named “inter-word writing interval”) did not have the same significance because participants were already engaged in the writing process (remember that they had already written the first word), and the cognitive load associated with target retrieving was less important than in Experiment 1 (the latencies were also shorter). Consequently, it is possible that spelling recovery of target words occurred in parallel with the graphomotor execution of the prime in Experiment 2, as has already been evidenced in eye movement recording ([Lambert et al., 2011](#)). The priming effect may thus be observed during the graphomotor execution of the prime rather than during the inter-word writing interval. These different task constraints modulated the availability of the cognitive resources required for processing the words, which, in turn, influenced the time course of morphologically complex word writing. This resulted in the different localization of the priming effect in the two experiments.

The other questionable point concerns the direction of priming effects. In Experiment 1, faster latencies were observed when the targets were preceded by a derived or a pseudo-derived prime. By contrast, in Experiment 2, the target's writing duration increased when the preceding word was related to the target compared to when the preceding word was unrelated. In other words, the central processes implemented during the processing of the derived or pseudo-derived prime add an additional processing cost when writing the target. This effect may seem counterintuitive at first glance, as one might consider that the first writing of a shared root (e.g., *chant* in *chanter*) should facilitate the writing of that same morpheme when it is embedded in the target (e.g., *chant* in *chanteur*). An explanation can be given for this effect. We assume that if the effect is related to root activation, it should also influence writing latencies, which was not the case in Experiment 2 (contrary to Experiment 1). Therefore, we make the hypothesis that this effect is likelier located further away in the word writing process. Related prime-target pairs shared the same first letters (i.e., roots or pseudo-roots, depending on the condition) but not the same last letters (i.e., suffixes or pseudo-suffixes). For example, the words *chanter* and *chanteur* share the root "chant" but have different suffixes ("er" vs. "eur"). When writing primes, skilled writers pre-activate both the root and the suffix in their orthographic lexicon (e.g., "chant" and "er" when writing "chanter"). Subsequent writing of the target word requires the inhibition of the previously activated suffix and the activation and writing of the appropriate suffix of the target (e.g., "eur" in "chanteur"). We assume that this inhibition-activation mechanism implies an additional processing cost that cascades from central to peripheral processes and, consequently, slows down the writing duration of targets.

In line with this explanation of the slowing-down effect, in the field of written word recognition, facilitating priming effects are only observed when the primes are derived words and the targets morphologically simple words (e.g., *chanteur-chant*) (Grainger et al., 1991). Studies that have used morphologically complex words as primes and targets have shown either an inhibition effect on target processing or an absence of the priming effect (Frost et al., 1997, Studies 1A and 1B). As Marslen-Wilson et al. (1994) explained, prime processing activates the root morpheme and the suffix, but, at the same time, "it inhibits other suffixed forms sharing the same stem" (Marslen-Wilson et al., 1994, p. 18). Therefore, the subsequent activation of the inhibited suffix necessarily implies additional processing time, which slows down the writing of the word. Further studies with other prime-target combinations and more precise measures for examining the writing dynamics of words are needed to support this hypothesis.

4.4. Theoretical implications

As pointed out by Lambert and Quémart (2019), the hierarchy of the different levels of word processing in written production has yet to be clarified, in particular the influence of morphological information in this process. The priming effects observed in our experiments provide further insights into the mechanisms involved in the production of morphologically complex words and shed light on the modeling of writing activity. The two experiments indicate that morphologically complex words are decomposed into constituent parts in production, which reinforces Quémart and Lambert's (2019) proposition that the orthographic lexicon is organized around morpheme units.

These experiments also indicate that such decomposition relies on the activation of a morpho-orthographic representation level. This result is comparable to what has already been reported in the field of spoken word production. The processing of morpheme units occurs independently of their meaning, which suggests that in the lexicon, morphemes are represented at the form level rather than at the semantic level. Dohmes et al. (2004) interpreted these results in the framework of Levelt's (1999) three-stage production model. Levelt proposed that information on a word's grammatical category is stored at the lemma level, while information on words' form properties (phonological and

morphological) is stored at the lexeme level. In word production, activation spreads from the conceptual level to lemmas and then, when the lemma is selected, the associated morphological and phonological codes are retrieved. According to Dohmes et al. (2004), such retrieval occurs without recourse to the meaning of morphemes. For example, when the lemma *corner* is activated in the memory, the lexical base *corn* and the suffix *-er* are also activated even though *corn* and *corner* are not related in meaning. Similarly, in written production, lemmas may activate the morphological units represented at the lexeme level. These lexemes are pre-activated regardless of whether the primes are derived or pseudo-derived, which then influences the processing of the related target.

Finally, we also need to interpret these results in tandem with the limitations of the study. First, as explained earlier, orthographic control words, namely monomorphemic words with no suffix-ending (e.g., *spinach* in English), are generally used in addition to pseudo-derived words in morphological priming studies. They would have allowed to confirm that the observed differences in writing latency (Experiment 1) and writing duration (Experiment 2) between the related and unrelated conditions were brought about not only by the shared letters between the prime and the target. To rule out this possible interpretation, we performed an additional analysis that indicates that the priming effects are not solely explained by orthographic overlap between primes and targets. Second, this study presents two experiments that used the priming paradigm in two different tasks. Experiment 2 addressed some limits of Experiment 1, especially by using a copying task to overcome the memory constraints involved in the learning-recall procedure. However, as both tasks were quite, comparing the results was difficult. For example, when copying the target word, the participants were already engaged in the writing process, which was not the case in the recall task. We have thus shown that the writing processes were not the same in the two tasks. These experiments and their limitations demonstrate the importance of conducting further studies with similar or other designs to better understand the processes involved in the writing of morphologically complex words.

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Declaration of competing interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.actpsy.2022.103670>.

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