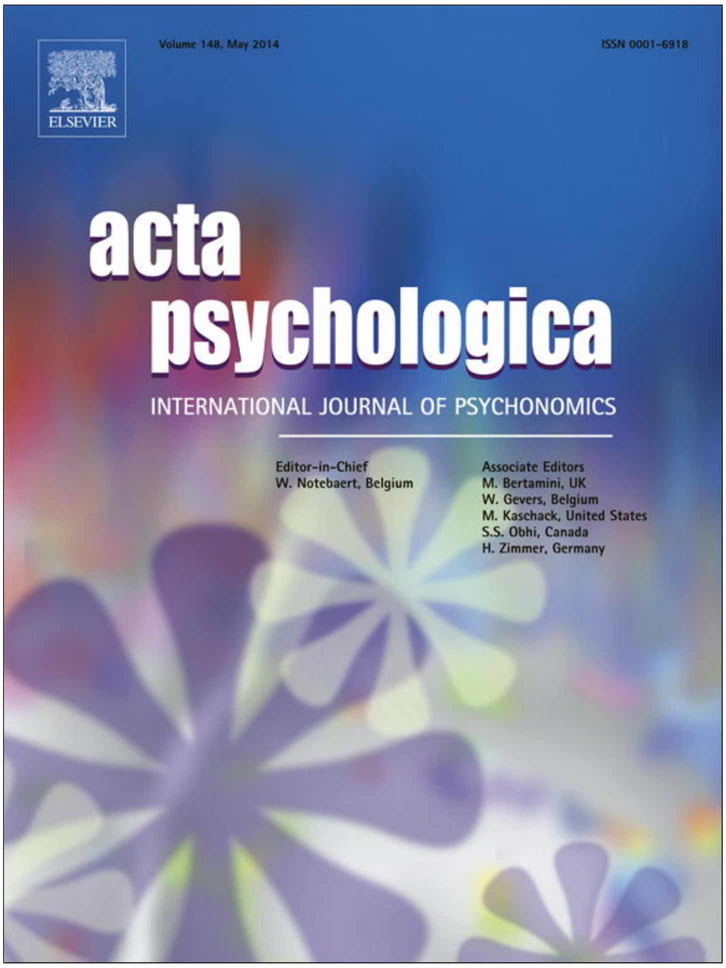
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How do we code the letters of a word when we have to write it? Investigating double letter representation in French

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ABSTRACT

How do we code the letters of a word when we have to write it? We examined whether the orthographic representations that the writing system activates have a specific coding for letters when these are doubled in a word. French participants wrote words on a digitizer. The word pairs shared the initial letters and differed on the presence of a double letter (e.g., LISSER/LISTER). The results on latencies, letter and inter-letter interval durations revealed that L and I are slower to write when followed by a doublet (SS) than when not (ST). Doublet processing constitutes a supplementary cognitive load that delays word production. This suggests that word representations code letter identity and quantity separately. The data also revealed that the central processes that are involved in spelling representation cascade into the peripheral processes that regulate movement execution.

1. Introduction

Knowing how to write is an essential skill in everyday life. To write a word, we recall its spelling and then write the letter string by producing hand movements with a pen/pencil. Most experimental studies on written word production have focused either on the spelling processes or on the motor production process. There has hardly been any interaction between the two approaches. This is quite surprising because to write a word needs both kinds of processes. First we have to recover its spelling from long term memory and then execute the movements to produce the writing. Research on spelling processes essentially used reaction time data to examine the spelling processes involved before we start to write (Afonso & Álvarez, 2011; Bonin, Peereman & Fayol, 2001; Qu, Damian, Zhang &, Zhu, 2011; Zhang & Damian, 2010). The studies on the motor aspects of written production investigated movement kinematics and considered writing as a manual movement, just like grasping or pointing movements. In this perspective, to write a word, we recall the shapes of the letters, activate the corresponding motor programmes and produce them following biomechanical and motor constraints (Teulings, Thomassen, Van Galen, 1983; Van Galen, Smyth, Meulenbroek, & Hylkema, 1989). According to Van Galen's (1991) model writing words involves the activation of its letter components in a linear fashion and, once the allograph is selected (Van Galen, 1991), we should always write a letter in the same way. Previous studies indicate, however, that spelling processes modulate motor process to optimize word production (cf. Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013; Delattre, Bonin, & Barry, 2006). The timing of motor production not only depends on the shape of the letter but also depends on the way the orthographic representations encode the letters for spelling recovery. Neuropsychological studies provide data suggesting that word representations code letter identity and order, of course, but are complex structures that also include syllable and letter doubling information (Caramazza & Miceli, 1990). The present study addresses the question of letter doubling. Most of us have written at least once a double letter in a word that is not the letter that has to be doubled (e.g., MISSING written MISINNG). What happens is that we know a letter in the word has to be doubled but we do not remember which one. Is there a special coding for double letters in orthographic representations? Case studies analysing the spelling errors of dysgraphic patients suggest that orthographic representations code letter identity and quantity independently (McCloskey, Badecker, Goodman-Schulman, & Aliminosa, 1994; Tainturier & Caramazza, 1996). However, we do not know what kind of information is actually being processed while we write. In the present research French participants wrote words on a digitiser that recorded the movements they produced while writing.

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The words had an embedded doublet (e.g., LISSER, to smooth) or not (LISTER, to list). We examined the effect of letter doubling before the participants started to write the word and while they wrote it.

1.1. Doublet coding in orthographic representations

The first studies on written language production assumed that the orthographic representations that we activate to write a word only code information on letter identity and order (Van Galen, 1991; Wing & Baddeley, 1980). The word MISSING for example would be represented as $M_1I_2S_3S_4I_5N_6G_7$. Neuropsychological studies soon argued against this linear conception of orthographic representations on the basis of the spelling performance of patients with a graphemic buffer disorder. Caramazza and Miceli (1990) presented the case study of an Italian dysgraphic patient LB, indicating that orthographic representations code letter identity and order but also other kinds of information like syllable structure and the letters' consonant/vowel status. They suggested that orthographic representations are multi-dimensional structures that code information on various levels of linguistic processing. LB's spelling errors also pointed to the idea that there could be a specific coding for double letters. The transposition errors of double consonants, unlike other consonant clusters, always involved a double consonant (e.g., TROPPO → PROTTO, but not PROTPO or PROPTO).

McCloskey et al. (1994) investigated double letter representation more deeply through a case study of an English-speaking dysgraphic patient. Their patient HE exhibited twice as many spelling errors for words with embedded double letters than for equivalent words without double letters. Furthermore, 83% of the errors in the words containing double letters concerned the doubled portion (e.g., CROSS → CROOS). The data globally indicated that letter identity and quantity are coded at different processing levels. This idea was also examined by Tainturier and Caramazza (1996) who suggested that double letters may behave as independent processing units. Their analysis of the spelling errors of another dysgraphic English-speaking patient indicated that double letters do not follow the same error patterns as letters that appear twice within a word but not in adjacent positions (e.g. CACTUS) or as letter chunks that represent a phoneme (e.g., ROCKET where CK = /k/). It is also noteworthy that the patient's spelling performance revealed that he preserved knowledge on the graphotactic rules that apply to letter doubling in English, since he never produced double consonants in word initial and only doubled the letters that can be doubled in English (e.g. never YY). This suggests that brain damage may selectively affect grapheme identity and grapheme quantity. It is worth mentioning that other neuropsychological studies also present case studies that support the idea that a letter is not coded in the same manner when it is doubled than when it is not (in Italian Miceli, Benvegnú, Capasso & Caramazza, 1995; Venneri, Cubelli & Caffara, 1994; and in English Ellis, Young & Flude, 1987).

Data on doublet representation from non-brain impaired individuals is scarce. Developmental studies on spelling acquisition provided evidence for a specific processing of double letters. In an experiment by Cassar and Treiman (1997), English-speaking first graders considered pseudo-words that had an embedded "legal" and frequent doublet (e.g., LL) as more word-like than pseudo-words that had an "illegal" doublet (e.g., HH). Further research conducted in French indicated that very early in the acquisition process the children are sensitive to the position of the doublet within the word. Pacton and colleagues (Danjon & Pacton, 2009; Pacton, Borchardt, Treiman, Lété, & Fayol, 2014; Pacton, Perruchet, Fayol, & Cleeremans, 2001; Pacton, Sobaco, Fayol, & Treiman, 2013) presented data in which first to fourth graders preferred pseudo-words that had the doublet in medial position like FOMMIR than pseudo-words with a doublet in initial position (e.g., FFOMIR, which is illegal in French). These studies suggest that the processing of double letters is different from the processing of the same letters in non-adjacent positions within the word. This kind of letter processing seems to be present very early, as soon as the children become familiar with written language. However, the authors do not refer to doublets as a level of coding in orthographic representations but rather to knowledge the children have on the statistical co-occurrence of letters in specific positions within words. As in the neuropsychological studies, the analysis in these experiments also relies on off-line measures and there is no information on how the knowledge on doublets modulates the writing process.

Several typing experiments investigating serial motor behaviour paid particular attention to letter doubling and provide on-line data on movement production. They measured the duration of inter-key intervals in consonant sequences that either contained double letters or not (Sternberg, Knoll, Monsell & Wright, 1983; Sternberg, Knoll, & Turock, 1990). The duration was a linear function of the number of elements in the sequence (e.g., SFCRZ > SFCR). For the sequences of equal length but containing double letters the durations were shorter than for the ones not containing double letters (e.g., SFCRZ > SCCRZ) and were equivalent to the durations of the sequences that contained four letters (e.g., SCCRZ = SFCR). The authors accounted for the data in terms of motor production. They were not concerned by orthographic representations and did not argue in favour of a specific level for double letter coding. They argued that duration decreased because the two elements of the doublet were processed as a single motor unit. However, Gentner (1987) reported data indicating that this speed gain is not systematic and depends on the location of the letter of the matched controls on the keyboard. Typing two letters with different hands was faster than producing a doublet with the same finger. The neuropsychological data together with these observations have been integrated in a computational spelling model that proposes a specific "geminate" node in its architecture (Glasspool & Houghton, 2005). It is also worth mentioning that letter chunking strategies in typewriting can be determined by the linguistic structure of word representations (Weingarten, 2005; Weingarten, Nottbusch & Will, 2004). Weingarten and colleagues reported evidence indicating that syllable and morpheme structure, among others, modulate the timing of typing movements. Many errors on letter doublets in everyday life are typewriting errors. Rumelhart and Norman (1982) discuss this kind of error and model it computationally. In their model they include a specific coding for doublets. When an error arises and the wrong letter is doubled it is because the doubling schemata were applied to the wrong letter. Doublets are processed differently because an activated letter needs to be inhibited to prevent perseveration. In the present study we examined whether the orthographic representations we activate for producing handwritten words code double letters and how they influence the motor production process.

1.2. Word representation in handwriting production

According to Van Galen's (1991) model word writing is the result of a series of processing modules that are organized in a hierarchical architecture. The higher order processing levels are common to the production of speech, typing and handwriting and were taken from Levelt's (1989) model of speech production. They concern concepts, semantic recovery and syntactic construction. Handwriting differs from speech at the level of spelling recovery, which is then followed by lower-order "motor" modules like allograph selection, size control and muscular adjustment. The higher-order levels – like the spelling module that processes orthographic representations – anticipate and process information related to forthcoming parts of the word in parallel to lower-order processing (e.g., local parameters such as letter size or movement velocity). When various representational levels are activated simultaneously, and because the writing system has limited capacities, movement production becomes more time consuming and duration increases. We focused on the interaction between the spelling and motor modules.

The model represents words as serial sequences that code information on letter identity and order (e.g., $L_1I_2S_3S_4E_5R_6$). Letters are programmed one after the other as they appear in the sequence in a linear fashion. However, recent studies provided evidence indicating that the process is far more complex. Kandel, Álvarez, and Vallée (2006) conducted an experiment in which French participants wrote words that shared the initial letters but had different syllable boundary positions (e.g., PRI.SON-PRIS.ME, the dot indicates syllable boundaries). The participants were instructed to write the words in upper-case letters so they could lift the pen between letters. The authors measured the duration of the interval between the letters (e.g., between I and S) located at the syllable boundary (e.g., PRI.SON) and at the corresponding serial position for the control word (e.g., PRIS.ME). The results revealed that inter-letter interval durations were longer between syllables than within syllables, indicating that word writing is not linear. It suggests a syllable-by-syllable writing strategy. The IS intervals were longer when they were located at the syllable boundary because the motor system anticipated the production of the following syllable. For within-syllable IS intervals the movement to produce the syllable had already been programmed before starting to write, so there was no need for further processing at this level. In a French–Spanish cross-linguistic study, the participants wrote cognates (i.e., words with similar spellings and meaning in both languages) with a letter sequence that was always intra-syllabic in French and inter-syllabic in Spanish (e.g. MA.GNOLIA and MAG.NOLIA, respectively). Again, the results showed that the inter-letter interval between G and N was systematically shorter in French than Spanish. This pattern of results also appears when French–Spanish bilinguals write the same items in French and Spanish. Therefore, letters are not produced in a linear fashion, one after the other, but are assembled into bigger chunks – i.e., syllables – that regulate motor programming during handwriting production, at least in syllable-timed languages.

This led Kandel, Peereman, Grosjacques, and Fayol (2011) to revisit Van Galen's approach. They proposed a model of handwriting production in which orthographic representations code letter identity and order but also other kinds of information that facilitate the programming of motor outputs. If we have to write the word MAISON (house) for example, we will segment the letter string into syllables (e.g., MAI_1SON_2). The information on the initial syllable is activated before starting to write (MAI_1). The following syllable is activated and programmed simultaneously to the production of the initial letters and up to the syllable boundary (SON_2). Then, the system considers information on letter co-occurrences because frequent bigrams lead to shorter writing times than infrequent ones. Some frequent bigrams have a special status because phonology can affect the way the writing system assembles letters into chunks. French complex graphemes like AI = /ε/in PRAIRIE (meadow), require a supplementary processing load with respect to simple graphemes such as A = /a/in CLAVIER (keyboard). Kandel and Spinelli (2010) reported that the durations were longer for the letter preceding the complex grapheme (R > L) and for its first letter (A). So in the example, MAI_1SON_2 would be represented as $M_1AI_2S_3ON_4$ at a lower level of orthographic representation since AI = /ε/and ON = /õ/. After bigram processing, we "unwrap" the word into consonant and/or vowel status ($C_1V_2V_3C_4V_5C_6$). This constitutes the input to the allograph module ($M_1A_2I_3S_4O_5N_6$), which will, in turn, decompose them into abstract letter shapes for allograph selection (e.g., M_1 = M or m).

In sum, research from various domains suggests that doublets could be coded at an independent level of orthographic representation and handwriting studies indicate that linguistic structure regulates word writing. The goal of the present study was to investigate this issue in handwriting production and provide on-line digitiser data on how and when this kind of orthographic coding affects movement production. French participants wrote words containing double letters (e.g., LISSER, Geminates hereafter). We compared their production to words that shared the initial letters but had no doublet (e.g., LISTER, Controls hereafter). If the orthographic representations the system activates when we have to write word code doublets (e.g., $L_1I_2SS_3E_4R_5$), the information on letter doubling should be activated before movement initiation. The processing of the doublet should be more time consuming than when there is no doublet (e.g., $L_1I_2S_3T_4E_5R_6$), so latencies should be longer in Geminates than Controls. Since central processing cascades into peripheral processes in handwriting we should also observe differences throughout the production of the word. Roux et al. (2013) reported data indicating that the central spelling processes are particularly active when we write the initial letters of the word. So letter durations and inter-letter intervals should also be longer in Geminates than Controls during the writing of the initial portion of the word until the processing of the doublet is completed. At the more local level – i.e., when the doublet occurs – we expected Controls to require longer durations than Geminates. If the orthographic representation of LISSER codes the doublet, the second S should be programmed beforehand. So when the S is actually being produced, the system should only process the local parameters required for letter production. In contrast, the programming of T in LISTER should not benefit from any specific anticipatory processing, so its production should be more time consuming.

2. Method

2.1. Participants

Twenty-seven 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. The study received approval from the ethical committee for Cognitive Science experiments in Grenoble. All the participants gave written consent for their participation in the experiment.

2.2. Materials

We selected a total of 32 French words (see Appendix A). Half of them contained a doublet or gemination (e.g., LISSER, Geminate words). We selected words containing the doublets SS, LL and RR because they are letters that are frequently doubled in French (24%, 23% and 9%, respectively; Catach, 1995). We matched them to words that shared the same initial letters but had no doublet (e.g., LISTER, Control words). French has predictable syllable boundaries (Noske, 1982). In spoken French LISSER is syllabified/li.se/ but orthographically the consonants of the doublet are spilt when writing (Catach, 1995). Thus, in LISSER there are two "ortho-syllables" LIS and SER. Kandel, Hérault, Grosjacques, Lambert, and Fayol (2009) reported handwriting data indicating that in French, children already at age 8 use orthographic syllables rather than phonological syllables when they write words. The Geminate words in our experiment had the syllable boundary between letters 3 and 4 (e.g., LIS.SER/LIS.TER; Catach, 1995). The words were also matched for bigram frequency at the position of the gemination. In the example, the bigram frequency of SS in LISSER is 1792 and of ST in LISTER is 1653 (bigram frequency always refers to the value by Type; Lexique 3.72 Data Base; New, Pallier, Ferrand, & Matos, 2001; http://www.lexique.org). The mean bigram frequency of the double letters was 1329 and the mean bigram frequency at the same serial position in the control words was 1215, $t(31) = .68$, $p = .49$. The first letter of the gemination was located at position 3 in the word (except for two word pairs in which it was at position 4: CHARRIER/CHARTER and COURROIE/COURTOIS). The mean word frequency for geminated words was 2.79 words per million, and the mean word frequency for control words was 3.75 words per million, $t(31) = .91$, $p = .36$. The words were 6 to 8 letters long, $t(31) = 1.71$, $p = .09$. Table 1 presents other matched variables.

Table 1
Characteristics of the words used in the experiment.

Experiment/variables	Geminates	Controls	*p* values (*t*-test)
Word frequency (pm)[a]	2.79	3.75	ns
Length (letters)	7.0	6.69	ns
Age of acquisition[b]	4.63	4.73	ns
Lexical neighborhood[a,c]	1.68	1.66	ns
Bigram frequency at the doublet position[a,d]	1309 (5390)	1196 (5358)	ns (ns)

[a] From the Lexique database (New et al., 2001).
[b] Estimated by an independent group of 15 students using a 7-point scale (1 = learned at 0–2 years and 7 = learned at age 13+, with 2-year age bands in between; Morrison, Chappell, & Ellis, 1997).
[c] As determined by the Levenshtein distance metric (Yarkoni, Balota, & Yap, 2008).
[d] Bigram frequency based on type counts (token count estimates in parentheses).

2.3. Procedure

The experiment was ran with Ductus (Guinet & Kandel, 2010), that is a software specifically conceived for handwriting experiments. At the beginning of each trial, the participants heard an auditory signal and saw a fixation point 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 instructed to write the word they saw as soon as it appeared on the computer screen. They were told 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. There were two practice items before the beginning of the experimental session. The participants were tested individually in a quiet room. The experiment consisted of 48 trials presented randomly in 4 blocks of 12 words. There were 16 filler items so that there was a higher proportion of words without a doublet. The whole session lasted 15 to 20 min.

2.4. Data processing

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. Letter duration referred to the time the participants took to write a letter. The duration measure concerned the time the pen was on the surface of the digitiser and excluded the time the pen was in the air. For example, T has two strokes but there is a pen lift between them: first we write the vertical line (stroke 1), then we lift the pen to produce the horizontal line on the top (stroke 2). The time of the pen lift is not included in the duration measure. We measured the duration of the initial letters of the word until the location of the doublet (e.g., for LISSER/LISTER: L1 = L, L2 = I, L3 = S, L4 = S and T). To investigate whether gemination processing cascades throughout the initial letters of the word, we had to compare the durations of letters that are made up of a different number of strokes (e.g. L = 2 strokes, I = 1, S = 3, T = 2). To control for this point, we normalised the duration values with respect to the number of strokes per letter. The stroke segmentation was determined on the basis of a previous up-stroke/down-stroke analysis of each upper-case letter of the alphabet (cf. see Kandel & Spinelli, 2010; Spinelli, Kandel, Guerassimovitch, & Ferrand, 2012 for details on this procedure). We also measured the duration of the intervals between the letters located at the initial portion of the words (e.g., I1 = LI, I2 = IS, I3 = SS and ST). The interval duration 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. Finally, latency concerned the time between the presentation of the word on the screen and the moment at which the participant started to write it (pressure > 0). Letter and interval durations provide information on how and when we write. Latency refers to the processes of spelling recovery and movement preparation that take place before movement initiation.

3. Results

This section presents the results calculated from letter stroke durations, interval durations and latencies. We conducted ANOVAs with word type (Geminates, Controls) as main within-participants factor, both by participants (F1) and by items (F2). For the analysis of stroke duration we included letter position as within-participants factor (e.g., for LISSER/LISTER: L1 = L, L2 = I, L3 = S, L4 = S and T). For the analysis of interval durations we included interval position as within-participants factor (e.g., I1 = LI, I2 = IS, I3 = SS and ST).

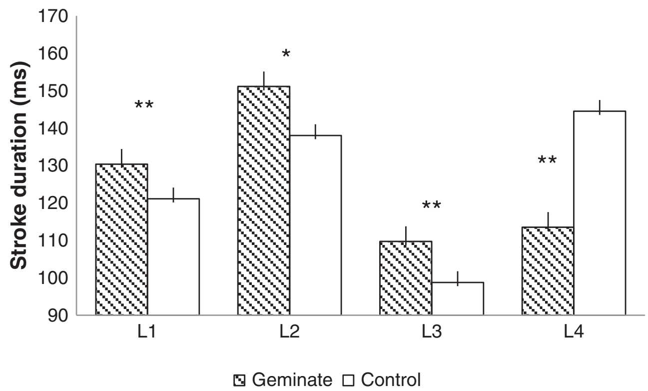

Fig. 1. Mean letter stroke durations for letters 1 to 4 in Geminates and Controls (e.g., LISSER/LISTER: Letter 1 (L1) = L, Letter 2 (L2) = I, Letter 3 (L3) = S, Letter 4 (L4) = S/T). For the pairs CHARRIER/CHARTER and COURROIE/COURTOIS, L1 corresponds to the second letter (H and O respectively), L2 corresponds to the third letter (A and U respectively), L3 corresponds to the fourth letter (R in both conditions) and, L4 corresponds to the fourth letter (R and T respectively). Bars represent standard error. The ** indicates that the duration difference between Geminate and Control words was significant for F1 and F2; * indicates that the difference was significant for F1 but not for F2.

3.1. Latency

Latencies higher than 3000 ms or below 300 ms were excluded (0.7% of the data). The remaining latencies that exceeded 2 standard deviations above or below each participant and item mean were also discarded (0.9% of the data). Mean latencies for Geminates were 1464 ms (SD = 408 ms) and 1380 (SD = 357 ms) for Controls. The analysis indicated that movement initiation was longer for geminates than controls, $F1(1, 26) = 7.54$, $p < .01$; $F2(1, 13) = 7.67$, $p < .01$.

3.2. Stroke duration

Fig. 1 presents the mean letter stroke durations for letters 1 to 4 for Geminate and Control words. Letter stroke durations that exceeded 2 standard deviations above or below each participant and item mean were discarded (0.7% of the data). The main effect of letter doubling was globally weak, $F1 < 1$; $F2(1, 15) = 6.42$, $p < .05$. Letter position yielded a significant effect, $F1(3, 78) = 95.65$, $p < .001$; $F2(3, 45) = 5.98$, $p < .001$. The interaction between the two factors was significant, $F1(3, 78) = 108.84$, $p < .001$; $F2(3, 45) = 9.86$, $p < .001$.

Pairwise comparisons revealed that the stroke durations for geminate words were longer than controls at all positions: for L1, $F1(1, 26) = 63.74$, $p < .001$; $F2(1, 15) = 7.08$, $p < .05$; for L2, $F1(1, 26) = 59.16$, $p < .001$; $F2 < 1$; for L3, $F1(1, 26) = 50.96$, $p < .001$; $F2(1, 15) = 8.45$, $p < .01$; and for L4, $F1(1, 26) = 82.52$, $p < .001$; $F2(1, 15) = 9.08$, $p < .01$. Furthermore, durations for L1 were shorter than L2, $F1(1, 26) = 53.55$, $p < .001$; $F2(1, 15) = 5.06$, $p < .05$; durations for L2 were longer than L3, $F1(1, 26) = 218.32$, $p < .001$; $F2(1, 15) = 15.01$, $p < .001$; durations for L3 were globally shorter than L4, $F1(1, 26) = 191.76$, $p < .001$; $F2(1, 15) = 20.95$, $p < .001$. In Geminates, durations for L3 and L4 were equivalent, both $F < 1$. In Controls instead, there was a significant increase from L3 to L4, $F1(1, 26) = 183.24$, $p < .001$; $F2(1, 15) = 14.73$, $p < .001$ (Bonferroni corrected).

3.3. Inter-letter interval duration

Fig. 2 presents the mean durations for intervals 1 to 3 for Geminate and Control words. Intervals that exceeded 2 standard deviations above or below each participant and item mean were discarded (0.1% of the data). Geminate words yielded longer interval durations than controls, $F1(1, 26) = 10.42$, $p < .01$; $F2(1, 15) = 14.62$, $p < .001$. Interval position did not reach significance. The interaction between the two factors was significant, $F1(2, 52) = 3.64$, $p < .05$; $F2(2, 30) = 4.69$, $p < .05$.

Pairwise comparisons revealed that the interval durations for geminate words were longer than controls only at positions 1 and 2: for I1, $F1(1, 26) = 9.78$, $p < .01$; $F2(1, 15) = 7.27$, $p < .01$; for I2, $F1(1, 26) = 14.07$, $p < .001$; $F2(1, 15) = 15.43$; and for I3, both $F < 1$.

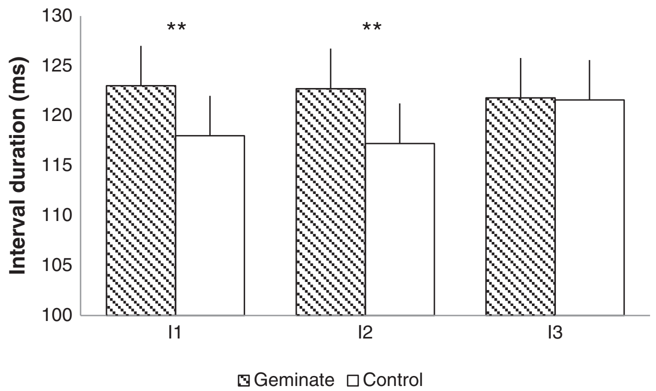

Fig. 2. Mean durations of intervals 1 to 3 in Geminates and Controls (e.g., LISSER/LISTER: Interval 1 (I1) = LI, Interval 2 (I2) = IS, Interval 3 (I3) = SS/ST). For the pairs CHARRIER/CHARTER and COURROIE/COURTOIS, I1 corresponds to HA in Geminates and OU in Controls, I2 corresponds to AR and OU respectively, I3 corresponds to RR and RT. Bars represent standard error. The ** indicates that the duration difference between Geminate and Control words was significant for F1 and F2.

4. Discussion

This study examined whether the orthographic representations the writing system activates when we have to write a word have a specific coding for double letters. We also investigated whether the processes that are involved in spelling recall cascade into the motor processes that regulate movement execution. The participants wrote Geminate (e.g., LISSER) and Control words (e.g., LISTER) on a digitizer. We measured latency (i.e., time before movement initiation), letter duration (e.g., L, I, S and S or T, respectively) and interval duration (e.g., LI, IS, SS or ST, respectively). The results on latencies revealed that spelling activation and movement preparation in Geminates took longer than Controls. Letter stroke and interval durations indicated that producing LIS in Geminates (LISSER) was systematically more time consuming than in Controls (LISTER). This suggests that orthographic representations code the presence of a double letter in a word. This occurred well before the letter is doubled and delayed movement production. The processing of the doublet information seems to require a supplementary cognitive load that delays the processing with respect to words that do not have double letters. The timing to produce exactly the same letters in a word (e.g., LIS in LISSER/LISTER) depends on the presence of a doublet embedded in the word, indicating that letter identity and quantity are coded independently. This data also revealed that doublet processing was active before movement initiation and cascaded into the processes that regulate motor production.

The stroke durations for the doubled portion in Geminates were equivalent. In Controls, instead, there was a significant increase from L3 to L4, such that at L4 durations for Controls were longer than Geminates. This suggests that the processing of the doublet was accomplished before starting to write it (Kandel et al., 2011; Van Galen, 1991), whereas the processing of L4 in controls was not. This is further evidence that in Geminates the information on the presence of the doublet was processed during movement preparation and throughout the production of the initial letters. Gemination processing at a central level spread onto peripheral processing until the first letter of the doublet. There was no duration increase in Geminates at L4 because, at the local level, producing the second S of LISSER, for example, required the repetition of the motor programme activated in L3. In Controls L4 required much more processing than in Geminates because it was not entirely programmed beforehand.

It is noteworthy that the L3–L4 position corresponds to the syllable boundary in all the words. L3 is the last letter of the first syllable and L4 is the first letter of the second syllable. The L4 duration increase observed in Controls is in line with French data reported by Kandel et al. (2009). In bi-syllables the authors found a systematic duration increase at the first letter of the second syllable. This indicates that the first syllable was programmed before starting to write and the second syllable was processed during the interval located at the syllable boundary and the production of the first letter of the second syllable.

The pattern of results was different for Geminates. The durations remained stable from L3 to L4. This suggests that the load generated by the presence of the double letters delayed the processing in such a way that the system could no longer adopt a syllable-by-syllable programming strategy as with Controls. This result therefore indicates that the presence of a doublet annuls the syllable-by-syllable writing strategy observed by Kandel et al. (2006, 2009). Kandel et al. (2011) reported data indicating that the "syllable effect" disappeared when i) a very low frequency bigram was embedded in the initial syllable; and ii) that its frequency was lower than the bigram located at the syllable boundary. Could the absence of syllable effect in geminate words be related to this? The mean frequency for bigrams 1 (e.g. LI in LISSER) and 2 (e.g. IS in LISSER) in geminates was 2813 and 2438, respectively (New et al., 2001). The mean bigram frequency for the doublet was 1329 (e.g. SS in LISSER). The frequencies of bigrams 1 and 2 were significantly higher than the frequency of bigram 3, $t(31) = 3.29$, $p = .004$ and $t(31) = 2.83$, $p = .01$, respectively. It is therefore unlikely that these results could be accounted for in terms of bigram frequency. Another possibility is that in French the syllabification for Gemination is different in spoken and written language. As mentioned above, phonologically speaking LISSER is syllabified/li.se/but orthographically it is LIS.SER (Catach, 1995). When French children have to deal with this kind of phonology/orthography conflict, there is a supplementary processing load that delays writing time. This is however, rather speculative, and the reason why doublet processing annuls the syllable effect in French should be investigated in future research.

The results are consistent with the idea that handwriting production functions in an anticipatory fashion, as posited in Van Galen's (1991) model. The writing system processed the doublet before starting to write and throughout the production of the letters that preceded it. They also support the idea put forward by Kandel et al.'s (2011) model that orthographic representations are multidimensional and code information on letter co-occurrence. Double letters are frequent bigrams in French but seem to represent a stronger cognitive load than complex graphemes (e.g., PRAIRIE). There are two reasons for this hypothesis. First, latencies, stroke and interval durations for Geminates were longer than in Controls, so doublet processing was initiated before starting to write and spread throughout the production of letters 1 to 3. Complex grapheme processing only affected the duration of the letter that preceded it (e.g., R in PRAIRE; Kandel & Spinelli, 2010). The second reason is that we did not observe a syllable effect in Geminates. Complex graphemes do not affect the syllable-by-syllable programming strategy, whereas the presence of a doublet disturbed the way the writing system processed syllable structure. These two points further support the idea that doublets receive a special coding and suggest that Kandel et al.'s (2011) model should locate doublet processing units higher in the hierarchy than complex graphemes. It is unclear however, whether doublet processing will take place before or in parallel to syllable activation. This should be tested experimentally in future studies.

Our experimental data confirm the neuropsychological findings with case studies (McCloskey et al., 1994; Tainturier & Caramazza, 1996). Orthographic representations code letter quantity and identity at different levels. We would like to point out that unlike English and Italian, in French there are no neuropsychological studies with dysgraphic patients indicating a particular coding of doublets in orthographic representations. Pacton et al. (2013) presented experimental data with children suggesting that French children have implicit knowledge on which consonants are doubled and the positions in a word where a doublet may occur. This data essentially concerned off-line measures, so there is scarce information on how letter doubling affects word writing on-line. Our digitizer measures allow us to go a step further because they tap into the locus of doublet processing. Doublet processing starts before movement initiation and ends when the doublet is actually written. This means that the effects of letter doubling are processed at a central level and cascade onto peripheral processing during movement execution. This implies a functional relationship between central and peripheral processes and shows the importance of studying word writing from an interactive perspective (Roux et al., 2013). Although the idea of cascading processing is not new, the studies on written production that integrate peripheral motor execution parameters and central linguistic factors are scarce.

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Appendix A. Geminate and control words

Geminate words			Control words		
	Word frequency (pm)	Critical bigram frequency		Word frequency (pm)	Critical bigram frequency
BASSINE	3.45	1792	BASCULE	6.32	588
CARREAU	7.58	865	CARTABLE	4.71	1103
CARRIER	1.71	865	CARCAN	1.61	771
CASSAGE	0.19	1792	CASTRER	1.39	1653
CASSEUR	0.94	1792	CASTEL	1.42	1653
CASSURE	2.19	1792	CASTOR	1.39	1653
CHARRIER	1.81	759	CHARTER	0.19	759
CORRECT	5.23	865	CORTEX	1.58	1103
COURROIE	2.19	1695	COURTOIS	5.06	1695
LISSER	0.9	1792	LISTER	0.58	1653
MARRON	9.68	865	MARTEAU	10.26	1103
MASSEUR	0.65	1792	MASTOC	0.32	1653
MISSILE	0.26	1792	MISTRAL	2.61	1653
PALLIER	2.74	1073	PALMIER	2.55	192
PARRAIN	5.1	865	PARTAGE	20.1	1103
SERREUR	0.03	865	SERTIR	0.06	1103
mean	2.79	1329	mean	3.75	1215

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