Journal of Experimental Psychology:
Human Perception and Performance
2011, Vol. 37, No. 4, 1310–1322

0096-1523/11/$12.00 DOI: 10.1037/a0023094

For a Psycholinguistic Model of Handwriting Production: Testing the Syllable-Bigram Controversy

Sonia Kandel
Laboratoire de Psychologie et NeuroCognition (CNRS UMR 5105), Université Pierre Mendès France, Grenoble, Institut Universitaire de France, Paris, GIPSA-lab, Département Parole et Cognition (CNRS UMR 5216), Grenoble, France

Ronald Peereman and Géraldine Grosjacques
Laboratoire de Psychologie et NeuroCognition (CNRS UMR 5105), Université Pierre Mendès France, Grenoble

Michel Fayol
Université Blaise Pascal, Clermont Ferrand, France

This study examined the theoretical controversy on the impact of syllables and bigrams in handwriting production. French children and adults wrote words on a digitizer so that we could collect data on the local, online processing of handwriting production. The words differed in the position of the lowest frequency bigram. In one condition, it coincided with the word's syllable boundary. In the other condition, it was located before the syllable boundary. The results yielded higher movement durations at the position where the low-frequency bigram coincided with the syllable boundary compared to where the low-frequency bigram appeared before the syllable boundary. Syllable-oriented strategies failed with the presence of a very low-frequency bigram within the initial syllable. Further analysis showed that children in grades 3 and 4 privileged syllable-oriented programming strategies. The production times of children in grade 4 were also affected by syllable frequency and, to a lesser extent, bigram frequency. The adults writing durations were modulated by bigram frequency. Therefore, both bigrams and syllables regulate handwriting production although the influence of bigrams was stronger in adults than children. In the light of these results, we propose a psycholinguistic model of handwriting production.

Keywords: handwriting, bigram frequency, syllable, adults, children

Writing a word is not just producing one letter after the other as if it was a mere linear sequence of letters. We tend to group the letters of a word into chunks (cf. Jenkins & Russel, 1952) to optimize the recovery of spelling. This chunking procedure has an influence on the way the writing system programs the movements to produce the letters of a word (e.g., Kandel, Álvarez, & Vallée-Hernández, 2006; Kandel & Spinelli, 2010). Recent research on handwriting production revealed that these letter chunks regulate the spatiotemporal aspects of the movement. French- and Spanish-speaking adult writers group letters into syllable-like chunks and program their handwriting movements syllable by syllable (Kandel et al., 2006a; Lambert, Kandel, Fayol, & Espéret, 2007; Kandel, Hérault, Grosjacques, Lambert & Fayol, 2009; Álvarez, Cottrell, & Afonso, 2009). Kandel et al argued that this syllable-oriented writing strategy supports the idea that syllables are an essential component of mentally represented orthographic structure (Kandel, 2009). This approach is strongly influenced by research on reading processes (see Rapp, 1992). An alternative interpretation—which also derives from studies on visual word recognition—is that this "syllable effect" could be due to the presence of low bigram frequencies at the word's syllable boundary. As Seidenberg et al proposed, a low bigram frequency at the syllable boundary displays a trough that produces the segmentation of the word into syllable chunks (Seidenberg, 1987; Seidenberg & McClelland, 1989). The present research examined the relative impact of bigram frequency and syllable structure in handwriting. French children and adults wrote words on a digitizer so that we could collect data on the local, online processing of handwriting production. The words differed in the position of the lowest frequency bigram. In one condition, the lowest frequency bigram coincided with the word's syllable boundary. In the other condition, the lowest frequency bigram was located before the syllable boundary. The contrast between the two conditions should allow disentangling the role of syllable structure and bigram frequency in handwriting.

The "early" studies on handwriting production assumed that we memorize words as linear sequences that code information on letter identity and order (e.g., Teulings, Thomassen, & Van Galen,

This article was published Online First April 18, 2011.

Sonia Kandel, Laboratoire de Psychologie et NeuroCognition (CNRS UMR 5105), Université Pierre Mendès France, Grenoble, Institut Universitaire de France, Paris, and GIPSA-lab, Département Parole et Cognition (CNRS UMR 5216), Grenoble, France; Ronald Peereman and Géraldine Grosjacques, Laboratoire de Psychologie et NeuroCognition (CNRS UMR 5105), Université Pierre Mendès France, Grenoble; and Michel Fayol, Université Blaise Pascal, Clermont Ferrand, France.

We are grateful to Lucie Hérault for her help in the experimental part of this work. We would also like to thank an anonymous reviewer for his/her enlightening comments that improved considerably the quality of this paper. This research was supported by a grant from the Région Rhône-Alpes (Cluster 11: Handicap, Viellissement et Neurosciences) attributed to Sonia Kandel.

Corresponding concerning this article should be addressed to Sonia Kandel, Laboratoire de Psychologie et NeuroCognition (CNRS UMR 5105), Université Pierre Mendès France, BSHM - B.P. 47, 38040 Grenoble Cedex 09, France. E-mail: Sonia.Kandel@upmf-grenoble.fr

1983; Van Galen, Smyth, Meulenbroek, & Hylkema, 1989). Van Galen (1991) thus proposed a model of handwriting production in which the orthographic representations of words simply encode information on letter identity and order. According to this view, the orthographic representation of the English word *anvil*, for example, would be represented as $A_1N_2V_3I_4L_5$. Kandel et al. (2006a) suggested that the handwriting system involves orthographic representations that are far more complex. Apart from letter identity and order, orthographic representations encode information from several sublexical processing levels such as morphemic (Kandel, Álvarez, & Vallée, 2008), syllabic (Kandel et al., 2006a; Lambert et al., 2007; Álvarez et al., 2009), and graphemic structure (Kandel & Spinelli, 2010). This "multi-dimensional" structure of orthographic representations (cf. Caramazza & Miceli, 1990) regulates the timing of handwriting programming.

The "Syllable" Hypothesis

Kandel et al. (2006a) provided evidence indicating that syllable structure regulates the timing of handwriting programming. In their study, French adults copied visually presented words on a digitizer. The words shared the initial letters but had different syllable boundaries (e.g., *tra.ceur* [tracer] and *trac.tus* [tract]; the dot indicates the syllable boundary). The participants had to write the words in upper-case letters and lift the pen between the letters. The assumption underlying this task was that the duration of the intervals between the letters provides information on the timing of motor programming. The results revealed that the between-syllable inter-letter intervals (between *a* and *c* in *tra.ceur*) were longer than within-syllable inter-letter intervals (between *a* and *c* in *trac.tus*). This syllable-by-syllable writing pattern was replicated with adults when writing words of various syllable lengths in French (Lambert et al., 2007) and Spanish (Álvarez et al., 2009). It is also noteworthy that this syllable-oriented writing strategies cannot be accounted for in terms of reading processes—the visual presentation of the word on the screen—because they also appeared with written picture naming and dictation tasks (Álvarez et al., 2009).

The duration increases at the syllable boundary can be explained in the framework of Van Galen's (1991) model of handwriting production, even if it supposes that orthographic representations only code information on letter identity and order. Its "anticipatory" conception of motor production is still the most efficient way of understanding the handwriting process. Van Galen's (1991) model postulates that handwriting is the result of a series of processing modules that function in parallel according to a hierarchical structure (Fig. 5). The "linguistic" modules—activation of intentions, semantic retrieval, syntactic construction—were taken from the model of speech production proposed by Levelt et al (Levelt, 1989, 1992; Levelt, Roelofs, & Meyer, 1999). They are common to all linguistic movements. Handwriting differs from speech at the spelling module. There is scarce information on how the spelling module functions. The words would be activated as whole units and then "unwrapped" into its letter constituents. The model did not consider any intermediate grained processing unit between words and letters. Then there are the "motor modules" that are responsible for allograph selection, size control, and muscular adjustment before the "Real time trajectory formation." The former are processing levels that are higher in the hierarchy than the more peripheral "motor" modules that regulate local parameters such as force, rotation direction, etc.

The processing modules are active simultaneously. The higher-order modules are active because they anticipate and process information related to forthcoming parts of the word, while the lower-order modules are involved in the processing of the local parameters. Because various modules of different representational levels are active simultaneously, and because processing capacities are limited, there is a supplementary cognitive load that results in an increase in movement duration. The duration increase observed by Kandel et al at syllable boundaries thus translates the parallel processing of the spelling of the following syllable and the local parameters of the current motor sequence. In other words, a significant duration increase at the syllable boundary indicates that the writing system programs the movement to execute the following syllable online, simultaneously with the processing of local parameters.

In a developmental perspective, Kandel & Valdois (2006) observed that this syllable-oriented writing strategies are present very early in the acquisition of written language. They provided data showing that French children in grades 1 to 5 (ages, 6 – 11) program the movements to write bisyllabic words and pseudowords syllable by syllable. As in adults, they observed systematic duration increases at the syllable boundary. In the word *vo.leur* (thief), for example, the movement time of the last letter of the first syllable (i.e., *o*) was shorter than the first letter of the second syllable (i.e., *l*) and the latter was in turn longer than the second letter of the second syllable (i.e., *e*). That is, the duration increase was located at the first letter of the second syllable (i.e., in *voleur* we observed that $o < l > e$). This pattern of results appeared at all school levels and regardless of item length and lexical status. The duration distribution throughout the whole letter string showed that the children programmed the first syllable before starting to write. Then they programmed the second syllable while producing its first letter. Since these duration increases at the syllable boundary appeared systematically in adults and children, Kandel et al called it the "syllable effect" (Kandel et al., 2006a; Kandel, Soler, Gros, & Valdois, 2006b; Lambert et al., 2007; Álvarez et al., 2009). They suggested that the writing system used a syllable-sized unit to chunk the letter string in a coherent—i.e., phonologically oriented—way that would facilitate the recovery of spelling.

Further research revealed that the syllables French children use as processing units when writing words have an orthographic rather than phonologic format (Kandel et al., 2009). The authors used a well known phenomenon observed in French words that end in *e*. These words are extremely useful for studying this issue because the syllabification is not the same in speech and written language. For example, the word *barque* (boat) is monosyllabic phonologically [baRk] but bisyllabic orthographically (*bar.que*). In the study by Kandel et al (2009), children in grades 3, 4, and 5 wrote words that were monosyllables phonologically but bi-syllables orthographically (e.g., *barque*). These words were matched to words that were bi-syllables both phonologically (e.g., *balcon* = [bal.kõ], balcony) and orthographically (e.g., *bal.con*,). The results on letter duration and movement dysfluency yielded significant increases at the syllable boundary for both types of words, indicating that the words were segmented according to graphosyllabic patterns rather than determined phonologically (i.e., exclusively derived from speech production processes). This is in agreement with neuropsychological data. The error patterns of dysgraphic patients exhibiting a "graphemic buffer disorder" revealed that orthographic representations code the graphosyllabic boundaries within the word; hence the name *grapho-syllable* or *ortho-syllable* (Caramazza & Miceli, 1990; Ward & Romani, 2000; see Olson & Caramazza, 2004 for data with deaf patients). Grapho-syllables obey the graphotactic constraints that define the combination of graphemic consonants and graphemic vowels (see Prinzmetal, Treiman, & Rho, 1986; Rapp, 1992 for more details). In addition, research on written word picture naming indicated that the spelling process may involve orthographic rather phonological codes (Bonin, Fayol, & Gombert, 1997, 1998).

The idea that grapho-syllables are processing units in handwriting production is in line with the syllable hypothesis proposed by studies on visual word recognition (Taft & Forster, 1976; Prinzmetal et al., 1986; Rapp, 1992; Ferrand, Segui, & Grainger, 1996; Álvarez, Carreiras, & Taft, 2001). These studies provide evidence that syllables are also relevant processing units in reading processes.

The Bigram or "Orthographic Redundancy" Hypothesis

The idea of a psychological reality of the syllable as a sublexical processing unit contrasts with Seidenberg's conception of visual word recognition processes (Seidenberg, 1987; Seidenberg & McClelland, 1989). This approach postulates that there is no sublexical orthographic unit at all. Readers would learn orthographic regularities as they get familiar with written language during the reading/writing acquisition period. In other words, they implicitly acquire information on the statistics of letter co-occurrence (Treiman & Zukowski, 1988; Perruchet & Pacton, 2006). This should render readers particularly sensitive to bigram frequency. Because within-syllable letters co-occur more frequently compared with between-syllable letters (Adams, 1981), we should also be particularly sensitive to syllable boundaries. In this perspective, the "syllable effect" could be accounted for in terms of bigram frequency.

The example that has been used in several papers on the syllable-bigram controversy concerns the word *anvil* (Prinzmetal et al., 1986). In *an.vil*, the within-syllable letter co-occurrences such as *an* and *vi* have bigram frequencies of 289 and 325, respectively. The bigram frequency of *nv*, located at the syllable boundary, has a bigram frequency of five. According to the "orthographic redundancy" hypothesis, the syllable segmentation pattern observed by Prinzmetal et al. (1986) and other researchers could be accounted for in "statistical rather than categorical" terms (Seidenberg & McClelland, 1989, p. 525). The participants would segment letter strings according to low-frequency bigrams and chunk letter strings according to high-frequency bigrams. According to this view, the perceptual processes would be mediated by orthographic redundancy. A low-frequency bigram at the syllable boundary would generate a trough that results in the segmentation of the word into syllable-like chunks.

Examining the Syllable-Bigram Controversy in Reading Processes

Rapp (1992), a tenant of the "syllable" approach, tested this hypothesis with English-speaking adults, using lexical decision and illusory conjunction paradigms (cf. Prinzmetal et al., 1986). The results exhibited syllabic effects that could not be accounted for in terms of the presence or absence of low-frequency bigrams. She stated that "the representation and manipulation of *abstract*, *symbolic*, *sublexical entities* forms an integral part of the process by which a written stimulus is identified by the reader" (p. 33).

Doignon and Zagar (2005) used the illusory conjunction paradigm to further examine this controversy in French visual word recognition. They presented words that differed in bigram frequency distribution according to two conditions (Fig. 1). In one condition, the bigram trough (i.e., the bigram with the lowest frequency) was located at the syllable boundary. In the other, the bigram trough was located within the initial syllable. In this condition, the frequency of the bigram at the syllable boundary was thus higher than the bigram located within the initial syllable.

Their results confirmed the syllable effect but also revealed a strong impact of orthographic redundancy. The syllable effect "was attenuated"—as the authors stated—when the bigram trough was located within the initial syllable and not at the syllable boundary. They concluded that ". . . results failed to show a pure syllabic effect as distributional properties of written language modulated the syllable influence, and they also failed to show a pure orthographic effect, as bigram boundaries only produced an effect when they coincided with syllable boundaries" (Doignon & Zagar, 2005, p. 454). The present research is in the continuity of Doignon & Zagar's (2005) study but in the area of handwriting production.

Examining the Syllable-Bigram Controversy in Handwriting Production

In the present study, we investigated whether the "syllable effect" observed by Kandel et al in handwriting production could be explained in terms of the word's bigram frequency distribution. In most of their experiments, they controlled for bigram frequency between conditions but they did not take into account the distribution of the bigram frequency *within* the letter strings of their corpora. Following Doignon & Zagar's (2005) experimental principle, the participants had to write words that differed in the position of the lowest frequency bigram (Fig. 1). The lowest

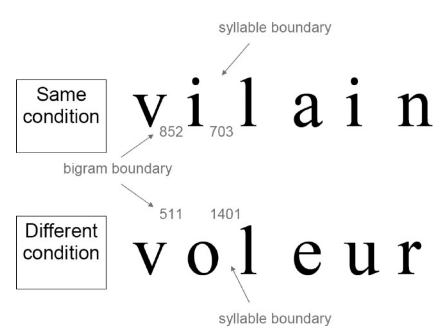

Figure 1. Example of the experimental manipulation. In the Same (S) condition (*vilain*) the frequency of the bigram located at the syllable boundary (*il*) is lower than the frequency of the bigram located within the initial syllable (*vi*). In the Different (D) condition (*voleur*) the frequency of the bigram located at the syllable boundary (*ol*) is higher than the frequency of the bigram located within the initial syllable (*vo*).

frequency bigram could either be located at the syllable boundary (the "Same" or S condition hereafter) or before the syllable boundary (the "Different" or D condition hereafter).

According to the "syllable hypothesis," we should observe longer movement durations at the syllable boundary than at the bigram position preceding the syllable boundary, irrespective of bigram frequency. In other words, in both the S and D conditions, the durations at the bigram position should be *shorter* than at the syllable position. In contrast, the "bigram hypothesis" predicts longer durations at bigram troughs, regardless of whether or not they are located at syllable boundaries. Therefore, as for the "syllable hypothesis," in the S condition, the durations should be *longer* at the syllable boundary (the lowest frequency bigram) than at the bigram position. Instead, in the D condition, the durations should be *longer* at the bigram position than at the syllable boundary. This means that there should be a crossover interaction, with longer durations at the within-syllable bigram in the D condition, and longer durations at the syllable boundary bigram in the S condition.

We conducted an experiment with children (experiment 1) and another with adults (experiment 2). Because children are more familiar with oral than written language, we expected that their writing strategies would be more influenced by phonology (i.e., syllable structure) than spelling regularities (i.e., bigram frequency). Thus, movement programming should be essentially regulated by the syllable structure of the words. This effect should be stronger in the younger children and should decrease as they grow up and become more and more familiar with spelling regularities. Because word spelling in adults is more consolidated than in children, the impact of the syllable structure could be attenuated by the use of writing strategies based on bigram frequency distribution. In this case, both syllable and bigram frequency effects might emerge in adults.

Experiment 1

In France, children are formally instructed to reading and writing skills at 6 years of age. Mojet (1991) showed that around 8 years of age, handwriting skills start to become automatic. This allows the child to focus more on spelling than on the motor aspects of handwriting production. With the repeated exposure to frequently associated letter groups, the spelling units also become more autonomous from phonological processes. Martinet, Valdois, and Fayol (2004) showed that at the beginning of reading/writing acquisition, French children privilege phonological strategies but start using orthographic information very early in the acquisition period (around 6 years of age). Therefore, children are particularly sensitive to phonological information but are also sensitive to orthographic regularity from the beginning.

As mentioned above, French children preferred using orthographic syllables rather than phonologic syllables even in grade 3 (i.e., at 8 years of age) (Kandel et al., 2009). This suggests that both phonological and orthographic processes contribute to movement programming in handwriting at this age. If the children chunk letters according to orthographic rather than phonological constraints, it is likely that they are also sensitive to letter co-occurrence. The "syllable effect" observed by Kandel et al could therefore be due to a lack of control of bigram frequency within and between syllables.

To examine the sensitivity of children to bigram frequency and syllable structure, we contrasted the "orthographic redundancy" and "syllable" hypotheses by comparing letter durations at within-syllable bigrams and between-syllable bigrams of different frequencies. Children in grades 3 and 4 (8 and 9 years old, respectively) wrote words that differed in the bigram frequency distribution (Fig. 1). The "syllable" hypothesis predicts letter duration increases at the syllable boundaries irrespective of bigram frequency. The durations should be longer at the syllable than at the bigram position. The durations in the S and D conditions should be equivalent. The "orthographic redundancy" hypothesis predicts higher letter durations at low-frequency bigrams compared with high-frequency bigrams. Thus, in the S condition, the durations should be longer at the syllable boundary than at the bigram position. In the D condition, the duration should be longer at the bigram than the syllable position.

Method

Participants. Thirty-four right-handed native French-speaking children participated in this experiment. There were 14 children from grade 3 (mean age: 8;3) and 20 from grade 4 (mean age: 9;7). They came from a public school in down-town Grenoble. They all had normal or corrected-to-normal vision and no motor disorders. They had parental consent to participate in the experiment.

Material. The corpus consisted of a total of 56 French bisyllabic words (Table A1). All the words were six letters long. We used the Lexique 2 French Data Base (New, Pallier, Ferrand, & Matos, 2001) as reference for bigram and word frequency data. Bigram frequency was computed as corresponding to the number of words that included the same bigram, at the same serial position. There were 24 words that had the syllable boundary at bigram 2 (e.g., between *i* and *l* in *vi.lain* which means naughty or ugly). In 12 of these words, the bigram at the syllable boundary was also the lowest frequency bigram in the initial syllable; the S condition. In *vilain*, for instance, the bigram frequencies are 852 for *vi* and 703 for *il*. These words were matched to words that had a low-frequency bigram occurring before the syllable boundary. In these words, the syllable boundary was at bigram 2 (e.g. *vo.leur,* thief) but the frequency of bigram 1 was lower than bigram 2; the D condition. For example, in *voleur* the bigram frequencies are 511 for *vo* and 1,401 for *ol*. The words in the S and the D conditions were matched for the initial letter and had equivalent word frequencies: 36.97 p.m. for the S words and 36.35 for the D words, $t(23) = 0.14$, $p = .89$. The remaining 32 words had the syllable boundary at bigram 3, that is, between letters three and four (*ver.ger*, orchard). In half of these words, the bigram at the syllable boundary was also the lowest frequency bigram occurring before the second syllable (S condition). In *verger*, the frequencies were 640 for *ve*, 2061 for *er*, and 428 for *rg*. These words were matched to words that had the syllable boundary at bigram 3 and shared at least the first letter (e.g. *vio.lon*, violin). In these words, either bigrams 1 (*vi* = 852) or 2 (*io* = 228) had a lower frequency than bigram 3 (*ol* = 415). These words corresponded to the D condition. The matched words had equivalent word frequencies: 5.40 p.m. for the S words and 6.18 for the D words, $t(31) = 1.42$, $p = .17$.

Procedure. The experiment was conducted with *Ductus*—a new handwriting software package recently developed in our laboratory for the study of handwriting production (Guinet & Kandel, 2010). Each word was presented in low-case Times New Roman size 18 on the centre of the screen of a laptop. Word presentation was preceded by an auditory signal and a fixation point for 200 ms. The child had to copy the word on the digitizer (Wacom Intuos3 A5 USB [PTZ-630], sampling frequency: 200 Hz, accuracy: 0.02 mm) that was connected to a computer that monitored the movement he/she executed. The children wrote the word on a lined paper that was stuck to the digitiser. The paper was like the one they usually use to write when they are in school (vertical limit = 0.8 cm and horizontal limit = 17 cm). The children were instructed to write the words "as usual"; i.e., in cursive handwriting. They became familiar with the material by writing their name and with two practice items. There were no time limit or speed constraints. Once they finished writing a word, the experimenter clicked on a button to present the following one. We prepared four sets of 14 words. To avoid exceeding the children's attention capacities, they were allowed to rest between two sets. We conducted the experiment individually in a room of the school.

Data analysis. Ductus also has a semiautomatic handwriting analysis module (see Guinet & Kandel, 2010 for information on the analysis procedure). Ductus smoothed the data with a Finite Impulse Response filter (Rabiner & Gold, 1975) with a 12-Hz cut-off frequency. Then, we segmented the words into their letter constituents by hand so we could obtain data on the timing of the movement that produced each letter (cf. Kandel & Valdois, 2006). Because the children wrote in cursive, the words were segmented into their letter constituents according to curvature maxima in the trajectory and velocity minima in the velocity profile. The duration measure concerned the time the children took to write each letter. To compare letters that are made up of a different number of strokes (e.g. *a* in *vilain* has three strokes and *e* in *voleur* has two strokes), we had to normalize the duration values with respect to the number of strokes per letter. For example, if the durations for both *a* and *e* are 180 ms, the mean stroke durations are 180/3 = 60 ms and 180/2 = 90, respectively. The normalization procedure was based on a segmentation procedure of cursive handwriting presented by Meulenbroek and Van Galen (1990). The results therefore refer to the normalized stroke duration. We compared the stroke duration values observed at the within-syllable bigram position and between-syllable bigram position for the S and D conditions.

Results and Discussion

We conducted an analysis of variance (ANOVA) with grade level (3, 4), condition (S, D), and boundary (bigram, syllable) as factors, both by participants (F_1) and items (F_2). Figure 2 presents the mean stroke duration at the bigram and syllable positions for the words in the S and D conditions. The analysis revealed that the durations for the S condition were higher than for the D condition, $F_1(1, 32) = 12.98$, $p < .001$, $\eta_p^2 = .28$; $F_2(1, 54) = 72.11$, $p < .001$, $\eta_p^2 = .03$. The bigram position yielded lower durations than the syllable position, $F_1(1, 32) = 19.22$, $p < .001$, $\eta_p^2 = .28$; $F_2(1, 54) = 7.45$, $p < .001$, $\eta_p^2 = .06$. Also, the durations for children in grade 3 were longer than for children in grade 4, $F_1(1, 32) = 10.54$, $p < .001$, $\eta_p^2 = .06$; $F_2(1, 54) = 72.11$, $p < .001$, $\eta_p^2 = .57$. The interaction between word type and letter position was significant only in the by-participants analysis, $F_1(1, 32) = 19.97$, $p < .001$, $\eta_p^2 = .38$; $F_2(1, 54) = 1.79$, $p > .05$, $\eta_p^2 = .03$. The interaction between the three factors did not reach significance in the by-items analysis, $F_1(1, 32) = 4.31$, $p < .05$, $\eta_p^2 = .11$; $F_2(1, 54) = 1.83$, $p = .18$, $\eta_p^2 = .03$.

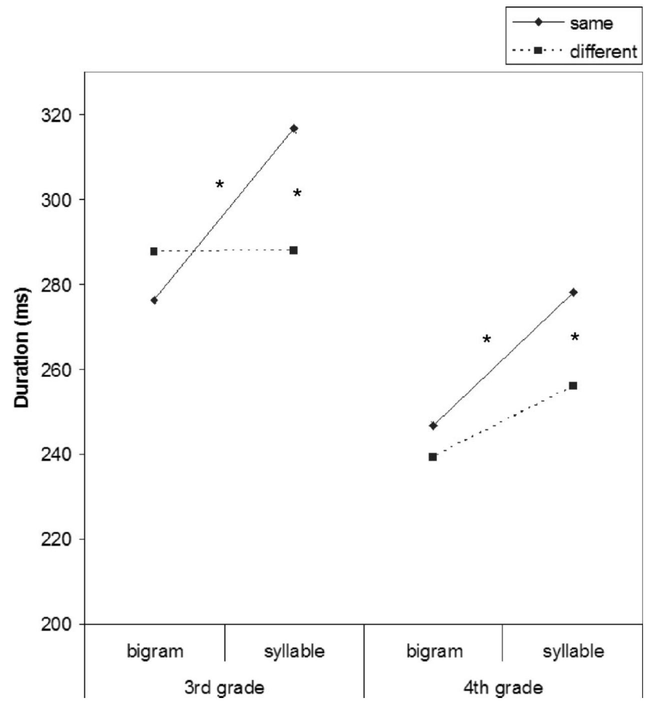

Figure 2. Mean stroke duration (ms) for children in grade 3 and 4 in the Same (S) and Different (D) conditions as a function of the position of the bigrams in the word. The Bigram position corresponds to the situation in which the bigram is located within the initial syllable. The Syllable position corresponds to the bigram located at the syllable boundary. The * indicates that the differences are significant both in the by-participants *and* by-items analyses.

Pairwise comparisons indicated that for children in grade 3, the duration of the S words for the bigram position was significantly lower than that for the syllable position, $F_1(1, 32) = 21.21$, $p < .001$; $F_2(1, 54) = 4.61$, $p < .05$. For the D words, there was no duration difference between the bigram and the syllable letter position, $F_1(1, 32) < 1$; $F_2(1, 54) < 1$. The difference between the S and D words was only significant at the syllable position, $F_1(1, 32) = 21.20$, $p < .001$; $F_2(1, 54) = 3.87$, $p < .05$. For the children in grade 4, the duration of the S words for the bigram position was significantly lower than for the syllable position, $F_1(1, 32) = 18.13$, $p < .001$; $F_2(1, 54) = 4.15$, $p < .05$. For the D words, there was a duration difference between the bigram and the syllable position but only in the by-participants analysis, $F_1(1, 32) = 4.64$, $p < .05$; $F_2(1, 54) < 1$. The difference between the S and D words was only significant at the syllable position and the latter did not reach significance in the by-items analysis, $F_1(1, 51) = 17.75$, $p < .001$; $F_2(1, 54) = 3.58$, $p = .06$.

In summary, stroke durations decreased with age. The durations for children in grade 3 were longer than those for children in grade 4, but the size of the effect was rather weak. This is in-line with previous work on handwriting acquisition and shows that the improvement of handwriting skills decreases movement production time (e.g., Kandel et al., 2009). Although the durations were different between the grades, the pattern of results was very similar. In the S condition, the durations were longer at the syllable boundary than at the within-syllable bigram boundary, as predicted by the syllable and bigram hypotheses. In the D condition, where the lowest frequency bigram was located within the initial syllable, there were no duration differences between the bigram and the syllable positions. This result does not support any of the two theoretical perspectives. According to the "syllable hypothesis," we would expect longer durations at the syllable boundary than at the bigram position, irrespective of bigram frequency. The results showed that when the lowest bigram frequency was not located at the syllable boundary, the "syllable effect" disappeared. Thus, the impact of syllable structure could be affected by bigram frequency. Following the rationale of the "orthographic redundancy" hypothesis, we would expect longer durations at the bigram than at the syllable positions. The results did not yield any duration differences between the within-syllable and between-syllable positions, revealing that bigram frequency did not regulate the timing of motor programming.

This pattern of results suggests that early in the writing acquisition period (third grade) the children are already sensitive to spelling regularities that derive from the probability of letter co-occurrence. Otherwise, we would have observed a pure "syllable effect". The fact that in the D condition the durations were equivalent at the bigram and syllable positions could also mean that the children adopted a bigram-by-bigram writing strategy but were not affected by the frequency of these bigrams. Further research would be necessary to elucidate this hypothesis. We could also hypothesize that the children used both bigram and syllable writing strategies. This possibility will be explored in the later section (the Supplementary analyses section).

The results indicate that the coincidence of the low-frequency bigram with the syllable boundary represents a greater cognitive load than when the low-frequency bigram is located before the syllable boundary. It is thus likely that for the words in the S condition, the children process simultaneously the presence of a low-frequency bigram and syllable boundary. In the D condition, the isolated presence of a low-frequency bigram or syllable boundary did not seem to produce a supplementary cognitive load, suggesting that it is the coincidence of both that affects the timing of handwriting programming.

This word programming pattern should be a reasonable strategy to acquire handwriting skills because —as pointed out by Adams (1981)—the probability of letter co-occurrence is generally lower at syllable boundaries than within boundaries. Does this programming strategy disappear with the automatization of writing skills or persists even in adults who have more experience with written language and are more familiar with the regularities of letter co-occurrence? The goal of experiment 2 was to investigate this issue.

Experiment 2

Experiment 2 used the same material as experiment 1 but was conducted with adult participants. We observed that in children, the coincidence of a bigram trough and a syllable boundary requires more processing than when there is no coincidence. Because the spelling of words is much more consolidated in memory in adults than children, it is likely that adults would rely more on orthographic regularities than on information about the presence of syllable boundaries. As in experiment 1, in the S condition, the bigram trough coincided with the syllable boundary (Fig. 1). In the D condition, the bigram trough was located before the syllable boundary. According to the syllable hypothesis, the durations of the S and D conditions should be similar, with longer durations at the syllable boundary than at the bigram position. According to the bigram hypothesis, we would expect longer durations at the syllable than bigram positions for the S condition and longer durations at the bigram than syllable boundaries for the D condition.

Method

Participants. Fourty right-handed individuals (mean age: 31 years old, 17 men and 23 women) 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.

Material. The words were exactly the same as in experiment 1 (Table A1).

Procedure. The procedure of this experiment was different from experiment 1 because the syllable effects observed by Kandel et al. (2006a) with adult participants concerned inter-letter intervals. We thus used the same procedure as they did so we could also provide data on inter-letter intervals.

Each word was presented in upper-case Times New Roman size 18 on the centre of the screen of a laptop. As in experiment 1, word presentation was preceded by an auditory signal and a fixation point for 200 ms. The participants' task was to copy the word on the digitizer (Wacom Intuos3 A5 USB [PTZ-630], sampling frequency: 200 Hz, accuracy: 0.02 mm) that was connected to the computer. The participants were instructed to copy the words in upper-case letters and lift the pen "naturally" between each letter (there were no particular instructions regarding the pen lifts). The height of the pen lift just consisted of a small wrist upward-downward movement of a few millimeters. They practiced the task by writing their names several times, until they thought they could do it spontaneously for the purposes of the experiment. Two practice items preceded the experiment. The participants had to start writing as soon as possible, but to write the words in their natural writing speed. There were no time limits or speed constraints. They had to write (with an Intuos Inking Pen) on a lined paper that was stuck to the digitizer (the vertical limit was 8 mm and the horizontal limit was 17 cm). The next item was presented once the participant accomplished the previous one. The 56 words were randomised and presented in four blocks of 16 stimuli. The experiment was conducted individually, in a quiet room and lasted approximately 30 minutes.

Data processing and analysis. As in experiment 1, Ductus smoothed the data with a Finite Impulse Response filter (Rabiner & Gold, 1975) with a 12 Hz cut-off frequency. For each item, we measured the duration of the intervals between the letters of the lowest frequency bigram within the syllable and at the syllable boundary. The interval was defined as the 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. In the words like *vilain-voleur*, we measured the interval between *v* and *i* or *o* for the bigram boundary and the interval between *i* or *o* and *l* for the syllable boundary. In the D words like *violon*, we measured the interval duration of the bigram boundary that corresponded to lowest bigram frequency in the initial syllable (between *i* and *o*). The syllable boundary corresponded to the interval between *o* and *l*. In the S words like *verger*, we measured the interval duration of the bigram position that corresponded to the same serial position as in the matched D word (between *e* and *r*). The syllable boundary corresponded to the interval between *r* and *g*.

Results and Discussion

Figure 3 presents the inter-letter interval duration (ms) at the bigram and syllable boundaries for the words in the S and D conditions. An ANOVA was conducted using condition (S, D) and boundary (bigram, syllable) as factors, both by participants (F_1) and items (F_2). The analysis revealed that the intervals at the syllable boundary were longer than those located at the bigram boundary, $F_1(1, 39) = 17.13$, $p < .001$, $\eta_p^2 = .30$; $F_2(1, 54) = 8.40$, $p < .01$, $\eta_p^2 = .13$. There was no condition main effect, $F_1(1, 39) < 1$, $\eta_p^2 = .002$; $F_2(1, 54) = 2.89$, $p = .09$, $\eta_p^2 = .05$. The interaction between the two factors was significant, $F_1(1, 39) = 9.72$, $p < .01$, $\eta_p^2 = .19$; $F_2(1, 54) = 10.52$, $p < .01$, $\eta_p^2 = .16$.

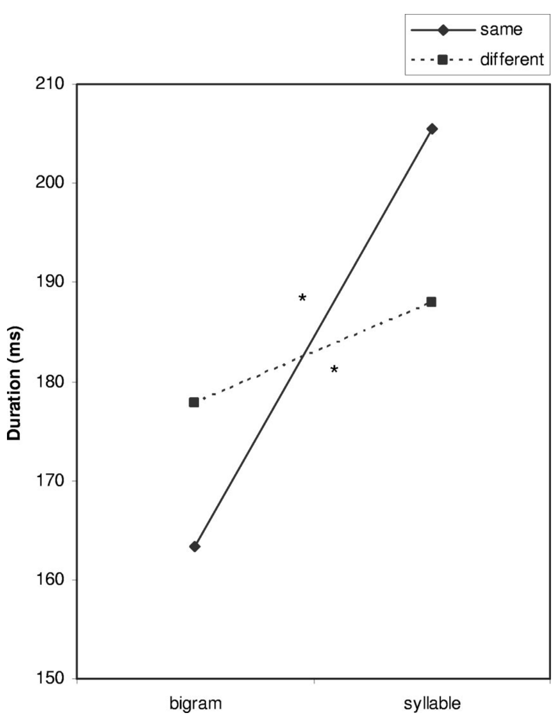

Figure 3. Mean stroke duration (ms) for adults in the Same (S) and Different (D) conditions as a function of the position of the bigrams in the word. The Bigram position corresponds to the situation in which the bigram is located within the initial syllable. The Syllable position corresponds to the bigram located at the syllable boundary. The * indicates that the differences are significant both in the by-participants *and* by-items analyses.

Pairwise comparisons indicate that the inter-letter intervals for the S words were longer when they were at the syllable than at the bigram positions, $F_1(1, 39) = 18.21$, $p < .001$; $F_2(1, 54) = 18.86$, $p < .001$. For the D words, there was no difference between the bigram and syllable boundaries, $F_1(1, 39) = 2.87$, $p = .09$; $F_2(1, 54) < 1$. At the bigram boundary, the inter-letter intervals in the D condition were longer compared with S condition, but the differences failed to reach significance in the by-items analysis, $F_1(1, 39) = 6.67$, $p < .01$; $F_2(1, 54) = 2.68$, $p = .10$. At the syllable boundary, the inter-letter intervals for the S words were longer than that for the D words, $F_1(1, 39) = 6.96$, $p < .05$; $F_2(1, 54) = 8.24$, $p < .01$.

The results globally show that in the S condition, the inter-letter intervals were longer at the syllable than at the bigram positions. This is in-line with the predictions of the syllable and bigram hypotheses. For the words in the D condition, there was no duration difference between the bigram and syllable positions. As in the experiment with children, the results fail to support any of the two theoretical approaches. Indeed, the "syllable effect" disappeared in the D condition, but bigram frequency distribution did not have a major impact on the way the participants regulated the timing of movement production. A minor impact can nevertheless be considered, because the durations at the bigram position were longer for the D than S words. This means that the processing of a low-frequency bigram was more time-consuming than a higher frequency bigram. However, these differences only reached significance in the by-participants analysis so further research should assess the impact of this effect.

To summarize, the co-occurrence of the lowest frequency bigram and the syllable boundary represents a supplementary cognitive load with respect to a situation in which there is no such coincidence. This suggests that syllable structure has an impact on the way the letter strings are produced, but the timing is conditioned by bigram frequency.

Supplementary Analyses

The general analyses in experiments 1 and 2 for the D condition are not concluding because they do not confirm the predictions of the syllable hypothesis or bigram trough. The observations for children and adults showed that when the syllable boundary did not coincide with the bigram trough (D condition) there were no duration differences between the syllable and bigram positions. This could indicate that syllable structure and bigram frequency determine movement durations in a competitive fashion. Additional analyses were therefore carried out to gain more understanding on the way syllable structure and bigram frequency affect the timing of handwriting production. The bigram and syllable frequency values for adults were computed from Lexique 2 (New et al., 2001), which is the same data base that we used for preparing the experimental material. We used Manulex_Infra (Peereman, Lété & Sprenger-Charolles, 2007) as reference data base for children because it is a database that exclusively refers to children's books.

We conducted multiple regression analyses to examine whether movement duration fluctuated according to bigram frequency and the presence/absence of a syllable boundary. The dependent variable concerned the durations at the syllable position for the Same words (i.e., the presence of a syllable boundary which, for adults, corresponds for example to the interval between *i* and *l* in *vilain*) and at the bigram position for the Different words (i.e., the absence of a syllable boundary corresponding to the interval between *v* and *o* in *voleur*). The presence/absence variable was coded 1/−1. The independent variable "bigram frequency" corresponded to the bigram frequency at the syllable position for the Same words and at the bigram position for the Different words. The results for adults indicated that bigram frequency modulates movement duration independently of the presence or absence of a syllable boundary, $B = -27.34$, $p < .01$. Indeed, the variable presence/absence did not exhibit a significant effect, $p = .61$. The analysis of the children data did not yield any significant effect: for children in grade 3, $B = -1.56$, $p = -.92$ and for the presence/absence variable $p = .25$; for children in grade 4, $B = -18.66$, $p = .14$ and for the presence/absence variable $p = .18$.

Because children in grade 4 exhibited a "tendency" towards significance, we examined the two variables plus the interaction between them with a stepwise regression analysis. We hypothesized that the influence of bigram frequency essentially depends on bigram position. This would imply that the presence of a syllable boundary overrules the impact of bigram frequency. This means that the interaction between bigram frequency and the presence/absence of a syllable boundary should be significant. For adults, the analysis confirmed that bigram frequency modulated movement duration regardless of the syllable boundary, $B = -30.29$, $p < .001$. For children in grade 3, there were no significant effects. However, for children in grade 4, the interaction was significant, $B = +7.35$, $p < .01$. This indicates that bigram frequency influences movement duration, but it depends on the presence of a syllable boundary.

We continued the analyses by investigating the impact of another variable that could influence movement duration, namely syllable frequency. Although we did not consider syllable frequency when we constructed the experimental material, we could suppose that the influence of syllable structure could be stronger when syllables are frequent than when they are infrequent. The calculations on syllable frequency used the same databases as earlier (i.e., Lexique and Manulex). In this analysis, the dependent variable concerned, as in the previous paragraph, the durations at the syllable position for the Same words and at the bigram position for the Different words. The independent variable also was bigram frequency. We added syllable frequency as independent variable. We attributed a zero to the situation when the bigram is not located at the syllable boundary (i.e., the Different words). By conferring a zero to the Different words, we suppose that the frequency of the initial syllable influences the durations at the syllable position (i.e., the Same words). The multiple regression results indicated that, as above, adults' durations were regulated by bigram frequency, $B = -27.22$, $p < .01$. Syllable frequency did not exhibit significant effects, $p = .56$. The analysis for children in grade 3 did not yield any significant effect of bigram or syllable frequency. For children in grade 4, we observed that bigram frequency did not affect movement duration ($B = -15.16$, $p = .20$) whereas syllable frequency did have an impact, $B = +21.40$, $p < .05$.

In sum, the analyses indicated that bigram frequency modulated movement duration in adults irrespective of syllable boundary position. This means that movement durations were longer for infrequent bigrams than for frequent bigrams. Because no significant effects were observed for children in grade 3, it is likely that bigram frequency starts influencing movement duration in children in grade 4 (i.e., around age 9), but the results revealed that this influence depends on the presence of a syllable boundary. The analyses further suggested that the frequency of the initial syllable has a greater impact on movement duration in children in grade 4 than bigram frequency.

Finally, since the analyses indicated that the durations at the bigram position were related to the corresponding bigram frequency, we re-examined the data of the D condition. The results of experiments 1 and 2 in the D condition yielded a lack of duration differences between the bigram and syllable positions. This could be due to a sort of "bigram attraction" for very low bigram frequencies and a "syllable attraction" for higher bigram frequencies. To verify this hypothesis, we divided the 28 items of the D condition into two groups according to their bigram frequency at the bigram position. The first group consisted of words presenting the lowest bigram frequencies at the bigram position and the second group consisted of words presenting the highest bigram frequencies at the bigram position. We conducted separate ANOVAs with Bigram frequency at the bigram position (Lowest, Highest) and Position within the word (Bigram, Syllable) as factors on mean durations in adults and children. The frequency of the first syllable was added as a covariate because it was shown to influence durations in children in the previous analyses. The results are presented in Figure 4.

The analysis for adults showed a significant interaction between Bigram frequency and Position, $F(1, 25) = 6.24$, $p < .05$. The durations were longer at the syllable position than at the bigram position for the highest bigram frequencies, $F(1, 12) = 5.14$, $p < .05$. The opposite trend appeared for the lowest frequency bigrams, $F(1, 12) = 4.18$, $p = .064$. For children in grade 4, the interaction between Bigram frequency and Position was almost significant,

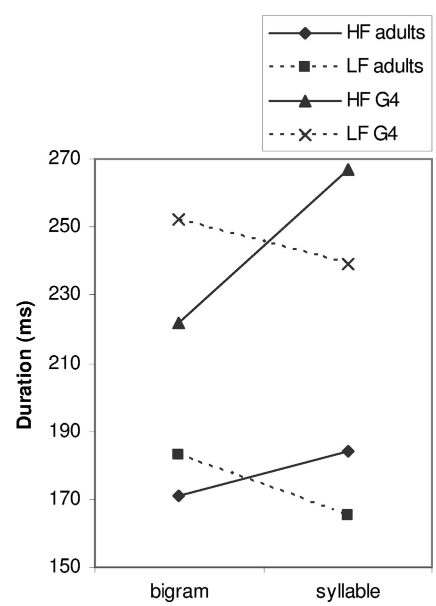

Figure 4. Mean stroke durations (ms) for children in grade 4 (G4) and inter-letter interval durations (ms) for adults in the Different (D) condition as a function of the position of the bigrams in the word. The dotted lines represent the durations for the low-frequency bigrams (LF) and the continuous lines represent the durations for the high-frequency bigrams (HF).

$F(1, 25) = 3.48$, $p = .074$. The durations were also longer at the syllable than at the bigram position for the more frequent bigrams, $F(1, 12) = 5.63$, $p < .05$ but, unlike adults, no opposite pattern was observed for the lowest frequency bigrams, $F < 1$. Finally, similar trends appeared for children in grade 3, but the interaction was far from reaching significance, $F(1, 25) = 2.45$, $p = .13$.

These results indicate that the presence of a bigram trough before the syllable boundary is not sufficient for ruling out syllable-oriented programming strategies. In both adults and children in grade 4, the durations at the syllable boundary were longer than at the bigram position for the highest bigram frequencies. This is in agreement with the predictions of the syllable hypothesis. However, when the within-syllable bigram frequency was low, the durations were longer at the bigram position than at the syllable position (for adults only). This is in agreement with the predictions of the orthographic redundancy hypothesis. So, once the syllable-by-syllable writing strategy is active, frequent bigrams will require less processing time than infrequent bigrams. Because the interaction for the children data did not reach significance, we may suppose that the children would be less affected by this phenomenon than adults.

General Discussion

This research investigated the bigram-syllable controversy in children (experiment 1) and adult (experiment 2) handwriting production. The participants had to write words that differed in the distribution of their bigram frequencies according to two conditions. In the S condition, the lowest frequency bigram coincided with the syllable boundary. The bigram frequencies of the initial syllable were thus higher than the bigram frequency at the syllable boundary (Fig. 1). In the D condition, the lowest frequency bigram was located before the syllable boundary. The bigram frequency at the syllable boundary was higher than at least one of the bigram frequencies located in the initial syllable.

In experiment 1, the stroke durations were longer for children in grade 3 than grade 4. This is in line with previous developmental data indicating that absolute duration decreases as the child grows up and handwriting skills become automatic (Meulenbroek & Van Galen, 1986, 1988, 1989; Mojet, 1991; Zesiger, Mounoud, & Hauert, 1993). The pattern of results was, nevertheless, very similar for both age groups. In the S condition, the durations were longer at the syllable boundary than at the bigram position. In the D condition, there were no duration differences between the two positions. It should also be mentioned that the differences between the S and D words were essentially observed at the syllable boundary. The durations in the S condition were longer than the D condition. The results of experiment 2 with adults yielded the same pattern of results as for children in grades 3 and 4. However, we observed a difference between the two populations at the bigram position, where the D words had longer durations than the S words. This difference should be interpreted with caution because it was only significant in the by-participants analysis.

The syllable hypothesis predicts that stroke durations should be longer at syllable boundaries than at any other position, irrespective of bigram frequency. Following this rationale, in the D condition, the durations should be shorter at the bigram than at the syllable position. The results of experiments 1 and 2 do not confirm these predictions. The bigram hypothesis predicts longer durations at bigram troughs, regardless of whether or not these bigrams are also syllable boundaries. In the D condition, we would thus expect longer durations at the bigram position than at the syllable position. Our results do not support these expectations either. They suggest that syllable boundaries and bigram frequency both contribute to the processing of the letter string. The results indicate that the coincidence of the bigram trough with the syllable boundary is more time consuming for the writing system than when the trough appears before the syllable boundary. The results for the D condition showed that a bigram trough in the initial syllable annuls the syllable effect. This means that bigram frequency affects the timing of handwriting programming in some way. However, the fact that the durations were equivalent, instead of modulated by bigram frequency as predicted by the orthographic redundancy hypothesis, means that syllable structure must also play some kind of role in the letter chunking procedure.

We conducted supplementary analyses to gain understanding on the respective roles of syllables and bigrams in handwriting production. When reconsidering the durations in the D condition, we realized that the nonsignificant difference between the durations at the bigram and syllable positions was due to the inverse duration patterns resulting from the processing of high and low-frequency bigrams (Fig. 4). In other words, when the bigram frequency of the trough was high, the durations were longer at the syllable position than at the bigram position. When the bigram frequency of the trough was low, the durations were shorter at the syllable position than at the bigram position. We can therefore conclude that both strategies are influential. This phenomenon seems to be absent in children in grade 3, suggesting that 3 years of explicit exposure to written language is not enough time to render the children sensitive to bigram frequency. The data suggest that bigram frequency starts affecting children's handwriting at grade 4, which corresponds to 9 years old.

The multiple regression analyses revealed that the impact of bigram frequency in durations for children in grade 4 depends on the presence of a syllable boundary. This suggests that the syllable boundary played a major role in the children's programming strategies but that the processing time for frequent bigrams was shorter than that for infrequent ones. Furthermore, syllable frequency had a stronger influence on the children's productions than bigram frequency. The analyses for the adult data indicate that their durations were more affected by bigram frequency than the presence of a syllable boundary and/or syllable frequency. Frequent bigrams required less processing time than infrequent bigrams, irrespective of syllable structure and frequency.

In summary, this study confirmed that children and adults tend to adopt syllable-by-syllable programming strategies, as showed by Kandel et al in previous research. The major finding is that although the letter strings were chunked into syllable units the durations in adults were also modulated by bigram frequency. Low-frequency bigrams required more processing time than high-frequency ones. The children's durations were mostly regulated by syllable frequency rather than bigram frequency. The influence of bigram frequency depended on the presence of a syllable boundary, and this was only observed in fourth grade. This suggests that when the grade 3 children wrote the words, they were essentially focused on syllable structure. Because the handwriting productions of children in grade 4 were also affected by syllable frequency, it is likely that the second step in the development of spelling skills in handwriting production would be to write frequent syllables faster than infrequent ones. The data also provide evidence that the children become more and more sensitive to bigram frequency as they grow up. They start in fourth grade, but the age at which bigram frequency overrules syllable structure and frequency is still to be determined in further research. The second important outcome of this study is that when the words contained a very low-frequency bigram within the initial syllable (the D condition), the programming strategies changed. Because the interaction almost reached significance, is likely that the timing of motor programming was regulated –to a certain extent– by bigram frequency.

Another point that deserves attention concerns the status of complex graphemes. Graphemes are the graphic representation of a phoneme such that the word *sea* for example is composed of graphemes S and AE because S = /s/ and AE = /i/ (Coltheart, 1978; Henderson, 1985). Simple graphemes concern phonemes that are represented by one letter (e.g., S = /s/) and complex graphemes refer to a phoneme that is represented by more than one letter (e.g., AE = /i/). Thus, two letter complex graphemes are phonologically determined. Furthermore, complex graphemes are always located within-syllables and not between-syllables. It is therefore likely that two letter complex graphemes are very frequent bigrams and unlikely that they constitute bigram troughs. This specificity is explicitly taught at school and orients the strategies the children have when writing words. Kandel et al., (2006b) showed that in first grade the children process the initial syllable grapheme by grapheme. In the word *chanson* (/ʃãsõ/, song), for example, they process the first complex grapheme CH = /ʃ/ then the second complex grapheme AN = /ã/ and then the second syllable SON = /sõ/ as a whole unit. As stated in the Introduction, adults' writing strategies are also modulated by grapheme structure (Kandel & Spinelli, 2010), indicating that bigrams that constitute complex graphemes are not processed as the other bigrams. In other words, because complex graphemes are frequent bigrams and are directly associated to phonology, they should have a special status in the processing of the letter string.

Our results are in-line with the ones presented by Doignon and Zagar (2005) for reading processes. There is a clear interaction between-syllable structure and bigram frequency. More research on this issue should be conducted, especially in other languages, since the impact of bigram frequency and the location of syllable boundaries on handwriting processing could vary as a function of the syllabification processes in languages. It is likely that in syllabic languages as Spanish (Harris, 1983) and French (Noske, 1982), the writing strategies would exhibit a stronger impact of syllable effects than languages like English in which syllabification is less clear and predictable (Seymour, Aro & Erskine, 2003).

Finally, this study supports the idea that the central spelling processes in handwriting production cascade on the more peripheral processes that are related to the motor aspects of the production process. As suggested by certain authors, this provides evidence that the production processing is not completely finished when the participant starts to write (Delattre et al, 2006; Álvarez et al., 2009; Kandel & Spinelli, 2010). This idea will be illustrated in the description of the model of handwriting, we propose in the following section.

For a Psycholinguistic Model of Handwriting Production

The data presented in this study support Van Galen's (1991) conception of handwriting production as a hierarchical and parallel processing cognitive task. The architecture of the model supposed that handwriting functions in a cascaded fashion. The processing of higher order tasks such as spelling recovery, which our study showed to be constrained by syllable structure and modulated by bigram frequency, functions in an anticipatory fashion. The anticipation of these processes is done in parallel to the processing of local parameters linked to letter production. This increases the processing load, resulting in an increase in movement duration. However, the data from these experiments also indicate that Van Galen's (1991) model—which claims that the orthographic representations of words are linear sequences of letters coding exclusively information on letter identity and order—should be revisited.

We propose to consider a spelling module that includes a series of sublexical units after the activation of the "linguistic modules" and before the "motor modules" (see Kandel, 2009). This would account for the impact of syllable structure and bigram frequency shown in the present study as well as recent research on handwriting processing. The orthographic representation of words would be conceived as multidimensional structures (cf. Caramazza & Miceli, 1990) that code information not only on letter identity and order but also on syllable structure and letter co-occurrences (bigrams and graphemes). Figure 5 presents a graphic representation of the way we believe the new model should look like. This conception of handwriting production, as Van Galen (1991), only concerns adult data.

We propose that the spelling module is a one route structure composed of various abstract processing levels that are active in parallel. To write a sequence we activate word representations that in turn activate syllables and letter components. The black arrows indicate that the processing levels function in a hierarchical manner. Bigger units should be activated before smaller units, so words should be activated before syllables, and the latter before letters. The syllable module encodes information on the syllable structure of words and in particular on the position of graphosyllabic boundaries. The letter module is an abstract processing level that stocks knowledge about letter co-occurrence (bigrams) as well as knowledge on the relationship between phonemes and letters (graphemes). The activation level of this processing module depends on bigram frequency. The outcome of the processing at the letter module serves as input to the following stage. The bigram and grapheme units are unwrapped into their letter constituents (letter identity and order). The individual letter identities are the input for the motor modules that are responsible of dealing with the parameters that regulate movement production per se. For example, the "Selection of allographs" module determines whether the letters of the word *vilain* will be written in cursive or script, upper-case or lower-case. The following modules take care of the more peripheral aspects of movement production like the calculations required for producing one letter after the other (see Orliaguet, Kandel, & Boë, 1997; Kandel, Orliaguet, & Viviani, 2000, for a description of the effects of calculating the spatial configuration of a following letter in handwriting production).

So to write the word *vilain*, a word of the S condition, in which the bigram trough is located at the syllable boundary, there is an activation of the orthographic representation of VILAIN (the capital letters

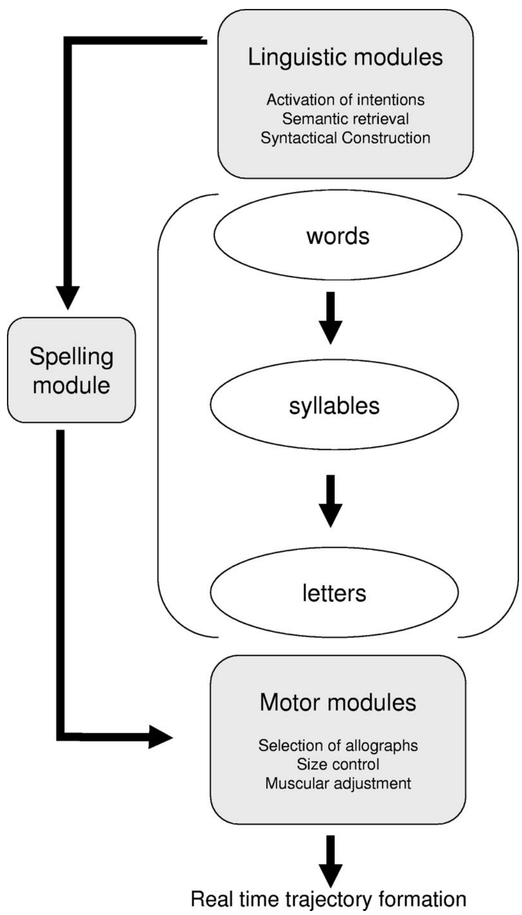

Figure 5. Graphic representation of the model we propose in the light of recent data on the spelling units used in handwriting production.

indicate that the processing is abstract and completely independent of the motor modules). This activation is followed by the activation of the syllable module, which informs the writing system that VILAIN = VI + LAIN. So VI is activated before starting to write. Then LAIN is activated on-line, in parallel to the letter and motor processing needed for the production of the initial syllable VI. At the letter level, activation thresholds are regulated by bigram frequency. So VI (bigram frequency = 852) will require less processing time than IL (bigram frequency = 703). The simultaneous processing of the following syllable together with the processing of an infrequent bigram generate a cognitive load that will go *in crescendo* towards the syllable boundary. This accounts for the results observed in the S condition, where durations were lower at the bigram position than at the syllable position. They also account for the words presenting a high-frequency bigram at the bigram position in the D condition, such as the word *voleur* (VO bigram frequency = 511, OL bigram frequency = 1,401). Note that this rationale also applies to words in the D condition presenting bigrams that are complex graphemes, like *auteur* (author, AU bigram frequency = 495, UT bigram frequency = 679). Understanding the way the writing system manages the interaction between letter co-occurrence and phonology is definitely a matter of further research.

The words presenting a low-frequency bigram at the bigram position in the D condition yielded longer durations at the bigram than the syllable position (e.g., *levain*, sourdough, LE bigram frequency = 211, EV bigram frequency = 451). The processing at the syllable module will result in LEVAIN = LE + VAIN. LE is activated before starting to write. Then VAIN is activated on-line, in parallel to the letter and motor processing needed for the production of the initial syllable LE. At the letter level, LE will require more activation to reach the threshold than EV. This will be time-consuming and thus increase movement duration at the bigram position. This duration is added to the duration increase resulting from the processing of the following syllable VAIN. So the duration will progressively decrease towards the syllable boundary. This explains why the durations are higher at the bigram than at the syllable position for very low-frequency bigrams in the D condition.

According to this view, learning how to spell would consist of integrating first a Syllable module and then a Letter module in the processing of handwriting. Children in grade 3 would only have a Syllable module. In grade 4 children, the activation of the syllable units in this module would depend on syllable frequency. As knowledge on letter co-occurrence (bigram) and knowledge on the relationship between phonemes and letters (graphemes) increases, the children would incorporate a Letter module that will overrule the influence of syllable frequency at a later stage of development.

Finally, it is possible that trigram frequency also plays a role in determining the activation level at the Letter module. Indeed, complex graphemes as *ain* in *vilain* are also frequent trigrams and Kandel and Spinelli (2010) provide data indicating that the writing system processes differently the production of *ai* and *ain*. Moreover, word endings such as some derivational morphemes as *eur* in *leveur* (a person who lifts weights) could be processed as word chunks that affect the timing of handwriting production (see Kandel et al., 2008).

References

Adams, M. J. (1981). What good is orthographic redundancy? In O. J. L. Tzeng & H. Singer, (Eds.), *Perception of print: Reading research in experimental psychology.* Hillsdale, NJ: Lawrence Erlbaum Associates Inc.

Álvarez, C., Carreiras, M., & Taft, M. (2001). Syllables and morphemes: Contrasting frequency effects in Spanish. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 545–555.

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

Bonin, P., Fayol, M., & Gombert, J. E. (1997). Role of phonological and orthographic codes in picture naming and writing: An interference paradigm study. *Current Psychology of Cognition, 16,* 299–320.

Bonin, P., Fayol, M., & Gombert, J. E. (1998). An experimental study of lexical access in the writing and naming of isolated words. *International Journal of Psychology, 33,* 269–286.

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

Coltheart, M. (1978). Lexical access in simple reading tasks. In G. Underwood (Ed.), *Strategies of information processing.* London: Academic Press.

Delattre, M., Bonin, P., & Barry, C. (2006). Written spelling to dictation: Sound-to-spelling regularity affects both writing latencies and durations. *Journal of Experimental Psychology: Learning, Memory and Cognition, 32,* 1330–1340.

Doignon, N., & Zagar, D. (2005). Illusory conjunctions in French: The nature of sublexical units in visual word recognition. *Language and Cognitive Processes, 20,* 443–464.

Ferrand, L., Seguí, J., & Grainger, J. (1996). Masked priming of words and picture naming: The role of syllabic units. *Journal of Memory and Language, 35,* 708–723.

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

Harris, J. H. (1983). *Syllable structure and stress in Spanish: A non-linear analysis.* Cambridge, MA: MIT Press.

Henderson, L. (1985). On the use of the term "grapheme". *Language and Cognitive Processes, 2,* 135–148.

Jenkins, J. J., & Russel, W. A. (1952). Associative clustering during recall. *Journal of Abnormal and Social Psychology, 47,* 818–821.

Kandel, S. (2009). For a psycholinguistic approach of handwriting production. *Advances in Graphonomics. Proceedings of the International Conference of the International Graphonomics Society,* Dijon, pp. 83–86.

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

Kandel, S., Alvarez, C., & Vallée, N. (2008). Morphemes also serve as processing units in handwriting production. In M. Baciu (Ed.), *Neuropsychology and Cognition of Language Behavioural, Neuropsychological and Neuroimaging Studies of Spoken and Written Language* (pp. 87–100). Kerala, India: Research Signpost.

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

Kandel, S., Orliaguet, J.-P., & Viviani, P. (2000). Perceptual anticipation in handwriting: The role of implicit motor competence. *Perception & Psychophysics, 62,* 706–716.

Kandel, S., Soler, O., Valdois, S., & Gros, C. (2006b). Graphemes as motor units in the acquisition of writing skills. *Reading & Writing: An Interdisciplinary Journal, 19,* 313–337.

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

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

Lambert, E., Kandel, S., Fayol, M., & Esperet, E. (2007). The effect of the number of syllables when writing poly-syllabic words. *Reading & Writing: An Interdisciplinary Journal, 21,* 859–883.

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

Levelt, W. J. M. (1992). Accessing words in speech production: Stages, processes and representations. *Cognition, 42,* 1–22.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22,* 1–38.

Martinet, C., Valdois, S., & Fayol, M. (2004). Lexical orthographic knowledge develops from the beginning of literacy acquisition. *Cognition, 91,* B11–B22.

Meulenbroek, R. G. J., & Van Galen, G. P. (1986). Movement analysis of repetitive behavior of first, second and third grade primary school children. In H. S. R. Kao, G. P. Van Galen, & R. Hoosein (Eds.), *Graphonomics: Contemporary research in handwriting* (pp. 71–92). Amsterdam: North Holland.

Meulenbroek, R. G. J., & Van Galen, G. P. (1988). The acquisition of skilled handwriting: Discontinuous trends in kinematic variables. In A. M. Cooley, & J. R. Beech (Eds.), *Cognition and action in skilled beh*avior (pp. 273–281). Amsterdam: North Holland.

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

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

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

New, B., Pallier, C., Ferrand, L., & Matos, R. (2001). Une base de données lexicales du français comtemporain: Lexique. *L'Année Psychologique, 101,* 447–462. (http://www.lexique.org)

Noske, R. (1982). Syllabification and syllable changing rules in French. In H. van der Hulst & N. Smith (Eds.), *The structure of phonological representations* (Vol. 2, pp. 257–310). Dordrecht: Foris.

Olson, A. C., & Caramazza, A. (2004). Orthographic structure an def spelling errors: Syllables, letter frequency, and speech. *The Quarterly Journal of Experimental Psychology, 57*A, 3, 385–417.

Orliaguet, J.-P., Kandel, S., & Boë, L. -J. (1997). Visual perception of cursive handwriting: Influence of spatial and kinematic information on the anticipation of forthcoming letters. *Perception, 26,* 905–912.

Peereman, R., Lété, B., & Sprenger-Charolles, L. (2007). Manulex-Infra: Distributional characteristics of grapheme-phoneme mappings, infralexical and lexical units in child-directed written material. *Behavior Research Methods, 39,* 579–589.

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: Two approaches, one phenomenon. *Trends in Cognitive Science, 10,* 233–238.

Prinzmetal, W., Treiman, R., & Rho, S. H. (1986). How to see a reading unit. *Journal of Memory and Language, 25,* 461–475.

Rabiner, L. R., & Gold, B. (1975). *Theory and application of digital signal processing.* Englewood Cliffs, NJ: Prentice-Hall.

Rapp, B. (1992). The nature of sublexical orthographic organization: The bigram trough hypothesis examined. *Journal of Memory and Language, 31,* 33–53.

Seidenberg, M. (1987). Sublexical structures in visual word recognition: Access units or orthographic redundancy? In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96,* 523–568.

Seymour, P. H. K., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology, 94,* 143–174.

Taft, M., & Forster, K. I. (1976). Lexical storage and retrieval of polymorphemic and polysyllabic words. *Journal of Verbal Learning and Verbal Behavior, 15,* 607–620.

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

Treiman, R., & Zukowski, A. (1988). Units in reading and spelling. *Journal of Memory and Language, 27,* 466–477.

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

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

Ward, J., & Romani, C. (2000). Consonant-vowel encoding and orthosyllable in a case of acquired dysgraphia. *Cognitive Neuropsychology, 17,* 641–663.

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

(*Appendix follows*)

Appendix

Table A1
Word and Bigram (B) Frequency

	Same Condition							Different Condition					
Word	Word Frequency	B1	B2	B3	B4	B5	Word	Word Frequency	B1	B2	B3	B4	B5
Action	205	1,186	**171**	1,666	577	2,295	Auteur	63	495	**679**	1,718	598	1,452
Aspect	78	884	**193**	836	415	554	Autour	245	495	**679**	912	2,213	1,452
Dehors	128	650	**27**	139	1,650	291	Demain	98	650	**797**	738	1,406	1,931
Hoquet	2	437	**150**	818	735	875	Homard	2	437	**1,845**	738	1,671	685
Logeur	0	521	**218**	314	598	1,452	Leveur	0	211	**451**	827	598	1,452
Loquet	2	521	**150**	818	735	875	Levain	1	211	**451**	532	1,406	1,931
Motard	2	1,495	**530**	1,206	1,671	685	Mutant	0	451	**679**	1,206	1,765	1,626
Orteil	1	474	**170**	1,718	234	1,385	Onglet	0	120	**467**	286	1,149	875
Pivert	1	807	**474**	827	2,810	698	Putois	1	452	**679**	912	499	2,185
Rajout	0	2,099	**126**	258	2,213	614	Rimeur	0	465	**473**	700	598	1,452
Regret	18	5,130	**204**	381	1,349	875	Rumeur	16	267	**383**	700	598	1,452
Villain	6	852	**703**	1,117	1,406	1,931	Voleur	8	511	**1,401**	611	598	1,452
Mean	37	1,255	**260**	842	1,199	1,044	Mean	36	397	**749**	823	1,092	1,495
Breton	14	1,092	734	**147**	960	2,295	Berger	13	355	2,061	**428**	621	2,794
Cactus	2	2,623	1,170	**413**	465	609	Chenil	2	1,962	286	**550**	636	1,385
Doublé	5	635	4,620	**133**	260	555	Diesel	8	1,746	337	**406**	1,167	632
Faucon	2	878	895	**631**	674	2,295	Fiston	1	630	1,575	**1,530**	960	2,295
Fripon	1	975	1,931	**247**	635	2,295	Fuyard	1	359	33	**158**	1,671	685
Guidon	4	323	714	**217**	340	2,295	Goulot	5	515	4,620	**706**	964	586
Grelot	1	1,159	734	**173**	964	586	Guenon	1	323	294	**550**	533	2,295
Harpon	1	692	3,419	**302**	635	2,295	Hindou	1	231	866	**993**	340	1,173
Marqué	24	2,342	3,419	**95**	1,001	235	Menton	32	517	1,826	**1,757**	960	2,295
Maudit	7	2,342	895	**364**	787	1,178	Mental	9	517	1,826	**1,757**	1,074	776
Ourlet	1	276	1,341	**249**	1,149	875	Oursin	1	276	1,341	**425**	920	1,931
Payeur	1	2,256	163	**92**	598	1,452	Peigné	1	1,162	321	**618**	481	350
Poupon	2	1,672	4,620	**374**	635	2,295	Poster	2	1,672	560	**1,530**	1,362	2,794
Sultan	13	1,896	503	**302**	1,074	1,661	Studio	13	692	90	**364**	787	598
Saumon	3	1,359	895	**229**	362	2,295	Slogan	2	29	596	**200**	214	1,661
Verger	6	640	2,061	**428**	621	2,794	Violon	8	852	228	**415**	964	2,295
Mean	5	1,323	1,757	**275**	698	1,626	Mean	6	740	1,054	**774**	853	1,534

Note. The upper panel concerns the 24 words that have the syllable boundary at bigram 2 (B2). The lower panel concerns the 32 words that have the syllable boundary at bigram 3 (B3). The numbers in bold refer to the bigram that is located at the syllable boundary. The frequency values were taken from Lexique 2 (New et al., 2001).

Received November 4, 2009
Revision received November 25, 2010
Accepted November 29, 2010 ■