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Graphemes as motor units in the acquisition of writing skills

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Abstract. This study examined whether the graphemic structure of words modulates the timing of handwriting production during the acquisition of writing skills. This is particularly important during the acquisition period because phonological recoding skills are determinant in the elaboration of orthographic representations. First graders wrote seven-letter bi-syllabic words on a digitiser. We measured movement duration and fluency and evaluated reading performance. In Experiment 1, the words varied in number of graphemes and grapheme structure. In Experiment 2, the words varied in graphemic structure but the number of graphemes was held constant. The results revealed that the children wrote the first syllable of the words grapheme-by-grapheme, irrespective of the number of letters that composed them. They prepared the movement to produce the first grapheme before starting to write. The following graphemes were processed on-line. They then prepared the movement to write the second syllable. The progressive decrease of duration and dysfluency values towards the end of the word indicates that the children prepared the entire syllable in advance. Movement time and dysfluency measures presented very similar patterns in the two experiments. Furthermore, there was a significant correlation between reading performance and handwriting measures. The grapheme and syllable structure of the words therefore modulates the timing of motor production during handwriting acquisition. Once the children have learned the phonological recoding rules, they apply them systematically, irrespectively of the size of the graphemes they have to write.

Key words: Children, Duration, Dysfluency, French, Graphemes

Introduction

To learn how to write, a child has to know which abstract linguistic symbols – letters – represent sounds of speech. Simultaneously, he/she develops the motor skills that produce the spatio-temporal realisation of letters. This study examined how the spelling of words, and in particular their graphemic complexity, mediates the kinematics of handwriting production during written language acquisition. To write the word *milk* (/milk/), for example, the child knows that /m/ = M, /i/ = I, /l/ = L and /k/ = K. There is a straight-forward relationship between the four phonemes and their graphemic counterpart. However, in the word *look* (/luk/), /l/ = L and /k/ = K, but /u/ = OO. There are three phonemes and four letters, so the mapping from sounds to letters is not a one-to-one operation, as in *milk*. This phenomenon occurs frequently in alphabetic languages, specially in those with deep orthographies like English and French (Seymour, Aro, & Erskine, 2003). This is why the term *grapheme* – the written representation of a phoneme – appears in the psycholinguistic literature (Berndt, Lynne D'Autrechy, & Reggia, 1994; Berndt, Reggia, & Mitchum, 1987; Coltheart, 1978; see also Venezky, 2004). Graphemes are considered as functional phonographic units (Peereman & Content, 1997) because they provide a more straightforward phonology-orthography association than letter-units.[1] The idea underlying this research is that, because in French there is often no direct mapping between sounds and letters, the handwriting production system has to rely on higher-order linguistic units like complex graphemes before activating single letters (Teulings, Thomassen, & Van Galen, 1983; Van Galen, Smyth, Meulenbroek, & Hylkema, 1989). If the handwriting production system uses the grapheme as processing unit, the graphemic structure of words should modulate the timing of motor production in handwriting processes. This should be particularly important during the acquisition period because phonological recoding skills are determinant in the elaboration of orthographic representations (Share, 1995, 1999; Sprenger-Charolles, Siegel, Béchennec, & Serniclaes, 2003).

The nature of orthographic representations

Handwriting involves different processing levels. From the intention of writing to the actual movement execution, there may be different modules that allow for semantic activation, syntax construction, spelling recovery, allograph selection, size control and muscular adjustment (Van Galen, 1991). These modules may communicate with one another. This study examined how the graphemic complexity of orthographic representations at the spelling module affects handwriting production. Adult neuropsychological research on patients presenting acquired dysgraphia indicates that orthographic representations at the spelling level are not mere linear sequences of letter strings. They are multi-dimensional because they store information on letter identity and order but also information of various linguistic representational levels such as the consonant and vowel status of letters and the syllabic structure of the word (Caramazza & Miceli, 1990; Caramazza, Miceli, Villa, & Romani, 1987; McCloskey, Badecker, Goodman-Schulman, & Aliminosa, 1994). Experimental studies also reveal that specific linguistic characteristics of orthographic representations affect the temporal and spatial features of handwriting production (Kandel, Alvarez, & Vallée, in press; Kandel & Valdois, 2005; Orliaguet & Boë, 1993; Orliaguet, Zesiger, Boë, & Mounoud, 1993; Wing, 1980). Kandel et al. (in press) showed, for instance, that in French and Spanish, two syllable-timed languages, adult writers produced their movements syllable by syllable. Several lines of research support the idea that between syllables and letters, grapheme-like units mediate written language processing.

Graphemes as processing units

Houghton and Zorzi (2003), in their connectionist model of spelling processes, proposed two distinct representational levels, one for grapheme-units (defined as the abstract representation of a phoneme), and another for letter-units. The system associates the phonemes to their graphemic counterparts before activating letter strings. For example, to spell the word *seat*, the system activates *s* + *ea* + *t* at the grapheme level and then *s* + *e* + *a* + *t* at the letter level. The model processes the grapheme *ea* as a unit at the grapheme level, providing a more straightforward mapping from phonology to orthography than if there was a direct mapping from sounds to letters. The authors showed that simulations of the spelling process are more accurate when considering both grapheme and letter levels than when excluding the grapheme level.

The second line of research concerns adult neuropsychological data. It supports Houghton and Zorzi's (2003) idea. Tainturier and Rapp (2004) analyzed the spelling performance of two English cases of acquired dysgraphia. Their spelling errors revealed that orthographic representations store information on two-letter graphemes that represent a single phoneme, as *ph* = /f/ in *phone*. This information is different from letter sequences that correspond to two phonemes as in the consonant cluster *pl* = /pl/ in *place*. The patients' performance indicates that complex graphemes have a unitary representation and are "unpacked" at the moment of serial production to specify letter identity and order. This view is in line with the idea that spelling involves two distinct processing levels (Houghton, Glasspool, & Shallice, 1994; Houghton & Zorzi, 2003; Rapp & Kong, 2002). The first level activates and keeps the orthographic information related to phoneme-letter correspondences in the buffer. The second refers to the identity and order of each letter that constitutes the buffered instructions for relating the orthographic information to the motor output, as required for production.

The third line of studies supporting the idea that graphemes are relevant processing units in written language processing comes from reading research (Dickerson, 1999; Joubert & Lecours, 2000; Martensen, Maris, & Dijkstra, 2003; Rastle & Coltheart, 1998; Rey & Schiller, in press; Rey et al., 2000; Venezky, 2004). Rey et al. (2000) carried out a study in French and English, in which the participants had to identify a target letter *a* embedded in a complex grapheme (*ea* in *beach*) or embedded in a word in which it appeared as a simple grapheme (*a* in *place*). Response times were systematically longer when the target letter was embedded in a complex grapheme than in a simple grapheme. The authors argued that response times were longer because it is harder to detect a target letter when it is embedded in a complex unit. The reading system has to split the unit into its constituents, which is more time-consuming. This splitting process is unnecessary in the case of simple graphemes. It is noteworthy that there was no lexical frequency effect, suggesting that the grouping of letters into complex graphemes is done automatically, at a sub-lexical level of processing.

In sum, the grapheme constitutes a processing unit in adult spelling and reading, supporting the idea that the handwriting production system could use grapheme-units as well. This hypothesis is particularly appealing in French because there are at least 34 graphemes of more than one letter (Catach, 1995). Although French phoneme-grapheme associations are less consistent than grapheme-phoneme ones (Peereman & Content, 1999; Ziegler, Jacobs, & Stone, 1996), the mapping from phonemes to graphemes to letters should still be more efficient than from phonemes to letters directly. We hypothesise that at the beginning of handwriting acquisition, the child learns to write strings of letters, but once he/she realises that a group of letters – a complex grapheme – represents only one phoneme, handwriting production should be mediated by grapheme-like units because they render letter-sound relationships more consistent. In other words, the graphemic structure of words should modulate the timing of motor production once the children start to apply phonological recoding skills because they use them to elaborate the orthographic representations that will serve as inputs for handwriting processes. So to write the word *look*, the child first activates /luk/, then decomposes it into its phoneme-grapheme units /l/ = L, /u/ = OO and /k/ = K, and finally "unwraps" the grapheme OO into its letter constituents for serial production.

Sub-lexical units in the acquisition of writing skills

This idea is based on research indicating that intermediate units between words and letters modulate the timing of children's handwriting production. Kandel and Valdois (in press a and b) have shown that in French sub-lexical units as the syllable modulate the timing of children's handwriting. First to fifth graders wrote visually presented words and pseudowords on a digitiser. A digitiser, or graphic tablet, is a sort of board that records the handwriting movements as a function of time (x and y coordinates as well as pressure intensity). Specific software then enables to calculate several parameters like duration, trajectory, velocity, etc. In Kandel and Valdois' (in press a), movement duration analysis revealed that the children prepared the movement to produce the first syllable before starting to write, and programmed the movement to write the second syllable during the production of its first letter. There was a duration increase at the first letter of the second syllable, and the duration then decreased progressively until the end of the word. For instance, the durations for *a* and *u* in the word *auto* were similar. Then, there was a significant increase at *t*, the first letter of the second syllable, followed by a decrease for *o*. This pattern of duration distribution was systematic, irrespective of lexical status, item length and grade level. The authors suggested that the children use the syllable as a unit for chunking information on the letter string in a coherent – linguistically oriented – way. This facilitates the recovery of orthographic information from the buffer at the spelling level of handwriting production. Then, the syllable is "unwrapped" into its letter constituents at the lower levels of the writing process. It is noteworthy that the authors used items of different graphemic complexities (e.g., *jouet* = /ʒue/ = 3 phonemes and *perdu* = /peRdy/ = 5 phonemes) and did not consider units smaller that the syllable, like complex graphemes. Graphemes should be relevant units in handwriting because children apply phonological recoding skills to elaborate the orthographic representations that will serve as input to the lower levels of the production process.

The present research aims at showing that, during the acquisition processes, graphemes constitute functional units for chunking orthographic information that will serve as input for motor production, together with syllables. To assess this issue, we asked first graders to write words of various graphemic complexities like *cris/tal* ([kRis/tal]) and *chan/son* ([ʃã/sõ]). These words have four and two graphemes, respectively, in the first syllable. We analysed movement duration and dysfluency, with particular attention at the grapheme and syllable boundaries.

The analysis of handwriting production

Movement time is used in most studies investigating the linguistic aspects of handwriting production (Bogaerts, Meulenbroek, & Thomassen, 1996; Kandel et al., in press; Kandel & Valdois, in press a and b; Meulenbroek & Van Galen, 1986, 1988, 1989, 1990; Mojet, 1991; Orliaguet & Boë, 1993; Van Galen, 1991; Van Galen, Meulenbroek, & Hylkema, 1986; Zesiger, Mounoud, & Hauert, 1993; Zesiger, Orliaguet, Boë, & Mounoud, 1994). According to Van Galen's (1991) model, handwriting is the result of a series of modules organised in a hierarchical structure. The linguistic aspects of handwriting are higher in the hierarchy than the more local parameters like size, direction and force. In this model, various modules can be active in parallel. The higher-order modules anticipate and process information related to forthcoming parts of the word while processing local parameters. When 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 and trajectory length. Some studies on children's handwriting also used movement dysfluency as an indicator of a supplementary processing load during parallel processing (Meulenbroek & Van Galen, 1988, 1990; Mojet, 1991; Zesiger et al., 1993). Dysfluency refers to the disturbances of the movement that appear in the velocity profile. When the handwriting movement is fluent, like in adults, the upstrokes and downstrokes have smooth velocity profiles, with one, or very few, velocity peaks. In young children, handwriting movements are quite dysfluent and thus characterised by an amazing number of velocity peaks for each stroke. The dysfluency in children's movements increases when concurrent processes – information from different representational levels – are active simultaneously.

Complex graphemes in the acquisition of writing skills

In the present study, we analysed movement time and dysfluency. If the children organise their writing movements grapheme-by-grapheme and then syllable-by-syllable, we should observe, for words like *cristal* and *chanson*, different duration and dysfluency patterns throughout the first syllable and similar patterns in the second one. For *cristal*, the duration and dysfluency should be stable throughout the first syllable, because the child produces four simple graphemes one after the other. For *chanson*, we expected the children to prepare the movement to produce the first complex grapheme before starting to write and the second one while finishing writing the first grapheme (i.e., at the second letter, in this case, *h*). There should be a duration and dysfluency increase at the second letter because of concurrent processing: calculating the local parameters and muscular adjustments to produce the *h* and programming the movements needed to produce the second complex grapheme. Then, for both words, there should be a duration and dysfluency increase at the first letter of the second syllable (*t* and *s*) due to parallel processing of the local aspects needed to produce the first letter and the programming of the movements to produce the end of the syllable. Finally, duration and dysfluency should decrease progressively until the end of the word because an important part of the processing has been done while producing the first letter and only the more local aspects of the movements need to be considered. We conducted this study longitudinally, examining first graders' writing behaviour seven and nine months after they were formally introduced to reading and writing skills. We expected the children to privilege a letter-by-letter strategy during the first months and then adopt a grapheme-by-grapheme strategy towards the end of the year, when phonological recoding skills become more automatic.

Experiment 1

Method

Participants

Thirty-four right-handed first graders participated in this experiment (20 girls and 14 boys). They were tested in March and May. Their mean age in March was 6;9, ranging from 6;3 to 7;2 (σ = 3;1). They were pupils from two schools of the Grenoble urban area, and their mother tongue was French. The teachers reported that the reading method was mixed. They used global and phonologic approaches simultaneously when teaching the children how to read and write. It should also be noted that French children learn to write in cursive handwriting from the beginning of the acquisition period. None of the participants was repeating or skipping a grade, and all were attending their grade at the regular age. They all had normal or corrected-to-normal vision and reported no hearing impairments. No learning disability, brain or behavioural problems were reported. School attendance was regular.

Material

The stimuli were 16 orthographically regular words (Appendix 1). The words were considered as orthographically regular when their letter string was composed of high frequency grapheme-phoneme correspondences (Catach, 1980). They were all seven letters long and bi-syllabic. We made sure that the children considered all the words as bi-syllabic by asking them to clap their hands each time there was a syllable. All the words had four letters in the initial syllable. In one condition they represented two graphemes (2 + 2 words henceforth) as in the word *chan/son* ([ʃã/sõ]), and in the other, four graphemes (1 + 1 + 1 + 1 words henceforth), as in the word *cris/tal* ([kRis/tal]). They were matched for lexical frequency, since Søvik, Arntzen, Samuelstuen, and Heggberget (1994) showed that 9 year old children produce lower movement durations when writing frequent words than less frequent words. Following the data provided by the *Lexique* French data base (New, Pallier, Ferrand, & Matos, 2001), word frequency means yielded 35.61 pm for 2 + 2 words and 29.93 pm for 1 + 1 + 1 + 1 words. Also, their mean bigram frequencies were 4691.51 and 3166.37, respectively. According to Content and Radeau's (1988) database, the mean bigram frequencies within the first syllable were 965.33 for 2 + 2 words and 862.50 for 1 + 1 + 1 + 1 words.

Procedure

The children saw each word on the centre of the screen of a laptop written in lower case Times New Roman size 18. An auditory signal and a fixation point (200 ms duration) preceded word presentation. Their task was to write the word on lined paper that was stuck to the digitiser (Wacom Intuos 1218, sampling frequency 200 Hz, accuracy 0.02 mm). The paper was like the one they usually used to write when they were in school (vertical limit = 0.8 cm and horizontal limit = 17 cm). The digitiser was connected to a computer (Sony Vaio PCG-FX203K) that monitored the handwriting movements. The children wrote the words "as usual" – i.e., in cursive handwriting, with a special pen (Intuos Inking Pen). They became familiar with the material by writing their name and with two practice items. There was 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 two sets of eight words to avoid exceeding the children's attention capacities, and they could take a rest between the two sets. The words were randomised across participants and the order of each set was counter-balanced. Children were tested individually in a quiet room inside the school. The experiment lasted approximately 20 minutes.

The children also went through a standard reading test, the Allouette (Lefavrais, 1967), to examine whether word segmentation is linked to reading performance, as shown by Kandel and Valdois (in press b). In addition, high reading performance is linked to the mastery of phonological recoding skills and spelling abilities (Share, 1995, 1999; Sprenger-Charolles et al., 2003). The reading test was conducted before or after the writing task (the order was counterbalanced).

Data analysis

The data were smoothed with a Finite Impulse Response filter (Rabiner & Gold, 1975) with a 12 Hz cut-off frequency. Since the children wrote in cursive handwriting, we used geometric and kinematic criteria to segment the words into their letter constituents. The beginning and end of each letter were determined by cuspids and 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. Dysfluency concerned the absolute velocity disturbances (i.e., the number of velocity extrema) per letter. When disturbances occur in the absolute velocity pattern, motoric impulses interrupt the ballistic manner in which a handwriting stroke is normally produced (Meulenbroek & Van Galen, 1988, 1990; Zesiger et al., 1993). Dysfluency values excluded the velocity dips at the borders of the cut segments. Since the number of strokes in each letter was different, we had to normalise duration and dysfluency values with respect to the number of strokes per letter, as in Bogaerts et al. (1996). For example, if the durations for an *l* (2 strokes) and a *b* (3 strokes) are both 180 ms, the mean stroke durations are 180/2 = 90 and 180/3 = 60 ms, respectively. The duration and dysfluency values of each letter were divided by the number of strokes it contained, according to a letter segmentation procedure presented by Meulenbroek and Van Galen (1990). Then, for each letter, we calculated the ratio of the mean stroke duration to the sum of all the mean stroke durations of the word, and then converted it to percentages. Likewise, we calculated the ratio of the mean number of velocity peaks in the letter to the total mean number of velocity peaks of the word, and then converted it to percentages. Letter duration and dysfluency percentages reveal information on the global organisation of the handwriting gesture because they provide information on the distribution of the duration and dysfluency throughout the entire word. With this procedure, we can see how duration and dysfluency increase or decrease at specific locations within the word. In addition, duration and dysfluency percentages allow comparisons among all participants, from very slow to very fast ones. For instance, the mean stroke duration of a given letter is 100 ms for one child and 200 ms for another, but the duration percentages are around 15%. This means that both children organise their handwriting movements in the same manner. This kind of analysis is very important for this study because the children's productions are observed longitudinally. Absolute duration and dysfluency decrease as the child grows up (Meulenbroek & Van Galen, 1986, 1988, 1989; Mojet, 1991; Zesiger et al., 1993).

Results

This section presents the results calculated from movement duration and dysfluency. Analyses of variance (ANOVA) were conducted using session, the number of graphemes in the first syllable and letter position as factors, both by participants (F_1) and items (F_2).

Movement time

The analysis of mean stroke duration percentages yielded a significant effect of letter position ($F_1(6,198) = 150.17$, $P < .001$; $F_2(6,84) = 16.27$, $P < .001$). The pattern of results was equivalent in both sessions. Figure 1 presents durations for 2 + 2 and 1 + 1 + 1 + 1 words in sessions 1 and 2.

The interaction between letter position and grapheme structure was significant ($F_1(6,198) = 27.45$, $P < .001$; $F_2(6,84) = 2.34$, $P = .03$). As Figure 1 shows, movement time analysis for the 2 + 2 words revealed two peaks at letters 2 (grapheme boundary) and 5 (syllable boundary). Letter duration percentages for the 2 + 2 words increased from letter 1 to 2 ($F_1(1,33) = 368.84$, $P < .001$; $F_2(1,14) = 17.34$, $P < .001$); decreased from letter 2 to 3 ($F_1(1,33) = 36.53$, $P < .001$; $F_2(1,14) = 4.72$, $P < .01$);

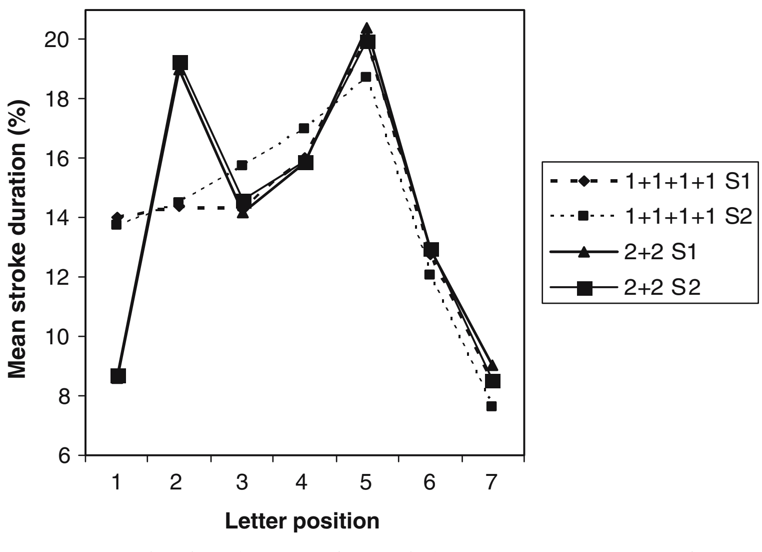

Figure 1. Mean stroke duration (%) for each letter in 1 + 1 + 1 + 1 and 2 + 2 words during sessions 1 (S1) and 2 (S2).

slightly increased from letter 3 to 4 ($F_1(1,33) = 4.59$, $P < .05$); then increased from letter 4 to 5 ($F_1(1,33) = 39.57$, $P < .001$; $F_2(1,14) = 14.35$, $P < .01$); and decreased again from letter 5 to 6 ($F_1(1,33) = 124.32$, $P < .001$; $F_2(1,14) = 21.76$, $P < .001$) and from letter 6 to 7 ($F_1(1,33) = 97.76$, $P < .001$; $F_2(1,14) = 18.94$, $P < .001$).

For the 1 + 1 + 1 + 1 words duration was rather stable throughout the first syllable. Duration percentages for letter 1 were equivalent to the ones observed for letter 2 and the scores for letter 2 were equivalent to the ones observed for letter 3. A slight increase was observed from letter 3 to 4 ($F_1(1,33) = 9.06$, $P < .01$). Then there was an important increase from letter 4 to 5 ($F_1(1,33) = 19.94$, $P < .001$) – which corresponds to the first letter of the second syllable – followed by a progressive decrease from letter 5 to 6 ($F_1(1,33) = 209.05$, $P < .001$; $F_2(1,14) = 22.08$, $P < .001$) and from 6 to 7 ($F_1(1,33) = 297.68$, $P < .001$; $F_2(1,14) = 20.92$, $P < .001$). Differences between the two types of words were only observed at letter 2 (grapheme boundary for the 2+2 words): 2+2 > 1+1+1+1 ($F_1(1,33) = 45.59$, $P < .001$; $F_2(1,14) = 15.18$, $P < .001$.

To see whether writing performance is linked to reading performance, we did correlations between reading level and total movement time to write the word (absolute duration values). The analysis revealed that the children with the best reading levels were the ones who took less time to write the words, $r(34) = -0.52$, $P > .05$ in the 1st session, and $r(34) = -0.61$, $P > .05$ in the 2nd session.

Finally, it is noteworthy that the children mostly adopted an analytic strategy for writing the words. Globally, only 15% of the 1 + 1 + 1 + 1 words and 12.5% of the 2 + 2 words were written without any gaze lift, i.e. without any pauses or gaze lifts to see the correct spelling on the screen.

Dysfluency

The analysis for velocity extrema revealed no significant effects for session and number of graphemes at the initial syllable. The effect of letter position was significant ($F_1(6,198) = 117.35$, $P < .001$; $F_2(6,84) = 15.00$, $P < .001$). Figure 2 presents the mean number of velocity peaks per stroke (%) in 2 + 2 and 1 + 1 + 1 + 1 words in both sessions.

The interaction between letter position and grapheme structure was also significant ($F_1(6,198) = 26.01$, $P < .001$). The dysfluency analysis for the 2 + 2 words revealed two peaks at letters 2 (grapheme boundary) and 5 (syllable boundary). Dysfluency percentages for the 2 + 2 words increased from letter 1 to 2 ($F_1(1,33) = 309.19$, $P < .001$; $F_2(1,14) = 12.52$, $P < .01$); then decreased from letter 2 to 3 ($F_1(1,33) = 33.79$, $P < .001$); remained stable from letter 3 to 4; then increased from letter 4 to 5 ($F_1(1,33) = 43.76$, $P < .001$; $F_2(1,14) = 5.02$, $P < .05$); and decreased again from letter 5 to 6

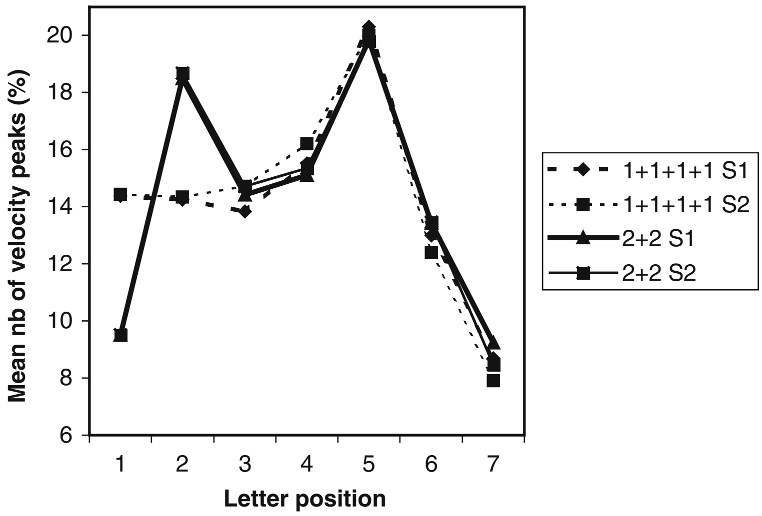

Figure 2. Mean number of velocity peaks per stroke (%) for each letter in 1 + 1 + 1 + 1 and 2 + 2 words during sessions 1 (S1) and 2 (S2).

($F_1(1,33)$ = 101.73, $P < .001$; $F_2(1,14)$ = 14.56, $P < .001$) and from letter 6 to 7 ($F_1(1,33)$ = 105.97, $P < .001$; $F_2(1,14)$ = 25.20, $P < .001$).

For the 1 + 1 + 1 + 1 words, the dysfluency values were very stable throughout the first syllable. Dysfluency percentages for letter 1 were equivalent to the ones observed for letter 2 and the scores for letter 2 were equivalent to the ones observed for letter 3. A slight increase was observed from letter 3 to 4 ($F_1(1,33)$ = 11.10, $P < .01$). Then there was an important increase from letter 4 to 5 ($F_1(1,33)$ = 32.83, $P < .001$; $F_2(1,14)$ = 4.37, $P < .05$) – which corresponds to the first letter of the second syllable – followed by a progressive decrease from letter 5 to 6 ($F_1(1,33)$ = 167.37, $P < .001$; $F_2(1,14)$ = 19.99, $P < .001$) and from 6 to 7 ($F_1(1,33)$ = 282.58, $P < .001$; $F_2(1,14)$ = 23.09, $P < .001$). Differences between the two types of words were only observed at letter 2 (grapheme boundary): 2 + 2 > 1 + 1 + 1 + 1 ($F_1(1,33)$ = 45.67, $P < .001$; $F_2(1,14)$ = 4.33, $P < .05$).

As with movement time, we examined whether writing performance was linked to reading performance. The analysis concerned correlations between reading level and total number of velocity peaks observed in the velocity profile of the word (absolute values). The analysis revealed that the children with the lower reading levels were the ones who had the most dysfluent movements, $r(34) = -0.63$, $P > .05$ in the 1st session, and $r(34) = -0.74$, $P > .05$ in the 2nd session.

Discussion

This experiment investigated whether first graders use graphemes as motor units during handwriting production. Duration and dysfluency measures exhibited very similar patterns, as in other studies using these measures. They are both indicators of a cognitive load due to parallel processing of information of different representational levels (Meulenbroek & Van Galen, 1988, 1990; Zesiger et al., 1993). In both sessions, there was a movement time and dysfluency peak at letters 2 and 5 for the 2 + 2 words. On the one hand, the duration and dysfluency peaks revealed that for the 2 + 2 words, the children prepared the movement to produce the first complex grapheme before starting to write. Data indicates that they processed the gesture to produce the second complex grapheme during the production of letter 2, and then they programmed the movement to write the second syllable during the production of letter 5, i.e., the first letter of the second syllable. These results match those obtained by Kandel and Valdois (in press a). On the other hand, for the 1 + 1 + 1 + 1 words, movement time and fluency were relatively stable throughout the first syllable, with a peak at letter 5. This suggests that the children processed the letters of the first syllable one by one. Since each letter represented grapheme, we can also speak of a grapheme-by-grapheme production. As with the 2 + 2 words, 1 + 1 + 1 + 1 words exhibited duration and dysfluency peaks at letter 5, indicating that the children prepared the movement to write the second syllable while processing the local parameters of its first letter.

In sum, the results yielded grapheme and syllable effects in both sessions and for the two types of kinematic measures. The children used grapheme units to produce the first syllable and syllable units to program the second syllable. We expected the children would exhibit a more letter-by-letter behaviour during the first session and then a grapheme-by-grapheme strategy during the second session, especially in the 2 + 2 words. The results did not confirm this hypothesis, since the children behaved similarly in the two sessions. If the first session was run earlier, may be there would have been differences. In any case, this suggests that once the children have learned that a phoneme is represented by several letters, as /ʃ/ = *ch* in *chanson*, they apply the conversion rule and use the grapheme as a unit during movement processing. This is supported by the significant correlations between reading performance and movement time and fluency. Moreover, the children mostly adopted an analytic strategy for writing the words.

In this experiment, the words had different graphemic structures but also a different number of graphemes. In the following experiment, we kept constant the number of graphemes and varied the graphemic structure.

Experiment 2

This experiment was designed to confirm the idea that the handwriting motor system activates grapheme-like units before processing the more local aspects of letter production (e.g., allograph selection, size control, muscular adjustments). In this experiment, the children wrote words containing two graphemes in the initial syllable, but the graphemic structure was different. In the first condition, they had two complex two-letter graphemes (*chan/son* [ʃã/sõ]), as in Experiment 1. In the second condition, the initial syllable started by a simple grapheme that was followed by a complex three-letter grapheme (as *pein/tre* [pɛ̃/tRə]; 1 + 3 words henceforth). For 2 + 2 words, we expected the same pattern of results for duration and dysfluency as in Experiment 1. For the 1 + 3 words, the motor system should prepare the movement to produce the first simple grapheme before starting to write. There should be a duration and dysfluency peak at the first simple grapheme because the system processes the local parameters of the letter production while processing the parameters needed to write the three-letter complex grapheme.

Method

Participants
The participants were the same ones as in the previous experiment.

Material
The stimuli were 12 regular, bi-syllabic, seven letter words (Appendix 2). There were four letters in the initial syllable. They represented two graphemes. In one condition, there were two two-letter graphemes (2 + 2 words), as in the word *chan/ter* ([ʃã/te]). In the other condition, the first grapheme was simple and the second one consisted of three letters (1 + 3 words) as in the word *pein/dre* ([pɛ̃/dRə]). The words were matched for lexical frequency, yielding means of 8.55 pm for 2 + 2 words and 8.75 pm for 1 + 3 words (New et al., 2001). The database also indicated that their mean bigram frequencies for the whole word were 5971.74 and 5285.64, respectively. According to Content and Radeau's (1988) database, the mean bigram frequencies within the first syllable were 1010 for 2 + 2 words and 584 for 1 + 3 words.

Procedure and data analysis
The procedure and data analysis was exactly the same as in Experiment 1. The 12 words were divided into two sets of 6 items. The experiment lasted approximately 15 minutes and was conducted in two sessions.

Results

This section presents the results calculated from movement duration and fluency. Analyses of variance (ANOVA) were conducted using session, grapheme structure of the first syllable (2 + 2 and 1 + 3) and letter position as factors, both by participants (F_1) and items (F_2).

Movement time
The analysis of mean stroke duration percentages yielded a significant effect of letter position ($F_1(6,198) = 83.75$, $P < .001$; $F_2(6,60) = 12.367$, $P < .001$). The pattern of results for the 1st and 2nd sessions was equivalent. Figure 3 presents mean stroke durations per letter (%) for 2 + 2 and 1 + 3 words in both sessions.

The interaction between letter position and grapheme structure was significant only in the by-participants analysis ($F_1(6,198) = 77.83$, $P < .001$). As Figure 3 shows, 2 + 2 words yield two duration peaks at letters 2 (grapheme boundary) and 5 (syllable boundary). Letter duration

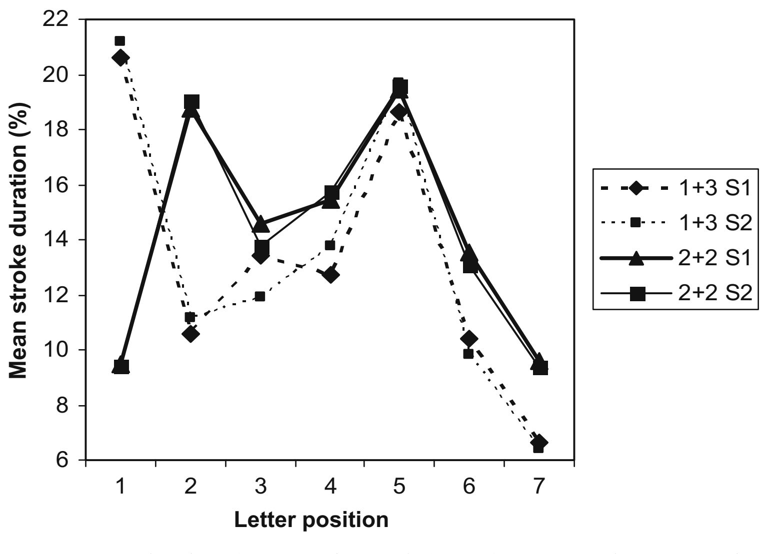

Figure 3. Mean stroke duration (%) for each letter in 1 + 3 and 2 + 2 words during sessions 1 (S1) and 2 (S2).

percentages for the 2 + 2 words increased from letter 1 to 2 ($F_1(1,33) = 272.07$, $P < .001$; $F_2(1,10) = 11.71$, $P < .01$); then decreased from letter 2 to 3 ($F_1(1,33) = 32.47$, $P < .001$). Duration percentages remained stable from letter 3 to 4 and then increased from letter 4 to 5 ($F_1(1,33) = 24.09$, $P < .001$). They decreased from letter 5 to 6 ($F_1(1,33) = 76.91$, $P < .001$; $F_2(1,10) = 11.03$, $P < .01$) and from letter 6 to 7 ($F_1(1,33) = 59.23$, $P < .001$; $F_2(1,10) = 18.58$, $P < .001$).

For the 1 + 3 words the pattern of duration distribution throughout the first syllable was different. Duration percentages for letter 1 were higher than for letter 2 ($F_1(1,33) = 161.74$, $P < .001$; $F_2(1,10) = 13.28$, $P < .01$). The percentages for letter 2 were equivalent to the ones observed for letter 3 ($F_1(1,33) = 1.58$; $F_2 < 1$) and from letter 3 to 4 ($F_1(1,33) = 2.03$; $F_2 < 1$). Then, there was a duration increase from letter 4 to 5 ($F_1(1,33) = 39.97$, $P < .001$; $F_2(1,10) = 10.93$, $P < .01$), followed by a decrease from letter 5 to 6 ($F_1(1,33) = 310.17$, $P < .001$; $F_2(1,10) = 23.47$, $P < .001$) and from 6 to 7 ($F_1(1,33) = 61.80$, $P < .001$; $F_2(1,10) = 13.58$, $P < .01$). Differences between the two types of words were observed at letter 1 (1 + 3 > 2 + 2 ($F_1(1,33) = 285.20$, $P < .001$; $F_2(1,10) = 21.08$, $P < .001$) and letter 2 (1 + 3 < 2 + 2 ($F_1(1,33) = 173.58$, $P < .001$; $F_2(1,10) = 13.36$, $P < .01$). Note that letter 1 corresponds to the grapheme boundary for 1 + 3 words and letter 2 corresponds to the grapheme boundary for 2 + 2 words.

As in Experiment 1, we did correlations between reading level and total movement time to write the word (absolute duration values). The analysis revealed that the children with the best reading levels were the ones who took less time to write the words, $r(34) = -0.49$, $P > .05$ in the 1st session, and $r(34) = -0.60$, $P > .05$ in the 2nd session.

Note again that only 10% of the 2 + 2 words and 13% of the 1 + 3 words were copied globally, without any gaze lift.

Dysfluency

As for movement duration, the analysis of velocity peaks revealed no significant effects for session and grapheme structure. The effect of letter position was significant ($F_1(6,198) = 87.07$, $P < .001$; $F_2(6,60) = 11.94$, $P < .001$). The interaction between letter position and grapheme structure was also significant ($F_1(6,198) = 82.12$, $P < .001$; $F_2(6,60) = 7.38$, $P < .001$). Figure 4 presents the mean number of velocity peaks (%) for the 2 + 2 and 1 + 3 words for both sessions.

Again, dysfluency analysis for the 2 + 2 words yielded two peaks at letters 2 (grapheme boundary) and 5 (syllable boundary). Dysfluency percentages for the 2 + 2 words increased from letter 1 to 2 ($F_1(1,33) = 224.56$, $P < .001$; $F_2(1,10) = 8.34$, $P < .01$); then decreased from letter 2 to 3 ($F_1(1,33) = 29.83$, $P < .001$); remained stable from letter 3 to 4; then increased from letter 4 to 5 ($F_1(1,33) = 30.77$, $P < .001$); and decreased again from letter 5 to 6 ($F_1(1,33) = 60.71$, $P < .001$; $F_2(1,10) = 6.69$, $P < .05$) and from letter 6 to 7 ($F_1(1,33) = 82.52$, $P < .001$; $F_2(1,10) = 23.75$, $P < .001$).

The 1 + 3 words exhibited a different pattern of dysfluency distribution. Dysfluency percentages for letter 1 were higher than for letter 2 ($F_1(1,33) = 170.05$, $P < .001$; $F_2(1,10) = 12.69$, $P < .01$). The percentages for letter 2 were equivalent to the ones observed for letter 3 ($F_1(1,33) = 1.61$; $F_2 < 1$) and from letter 3 to letter 4 ($F_1(1,33) = 2.71$; $F_2 < 1$). Then, there was a dysfluency increase from letter 4 to 5 ($F_1(1,33) = 56.44$, $P < .001$; $F_2(1,10) = 11.82$, $P < .01$), followed by a decrease from letter 5 to 6 ($F_1(1,33) = 18.96$, $P < .001$; $F_2(1,10) = 23.47$, $P < .001$) and from 6 to 7 ($F_1(1,33) = 15.72$, $P < .01$; $F_2(1,10) = 13.58$, $P < .01$). Differences between the two types of words were observed at letter 1 (1+3 > 2+2 ($F_1(1,33) = 261.94$, $P < .001$; $F_2(1,10) = 16.85$, $P < .01$) and letter 2 (1+3 < 2+2 ($F_1(1,33) = 153.60$, $P < .001$; $F_2(1,10) = 12.80$, $P < .01$). Note again that letter 1 corresponds to the grapheme boundary for 1+3 words and letter 2 corresponds to the grapheme boundary for 2+2 words.

Again, we did correlations between reading level and total number of velocity peaks observed in the word's velocity profile (absolute values). The analysis revealed that the children with the lower reading levels were

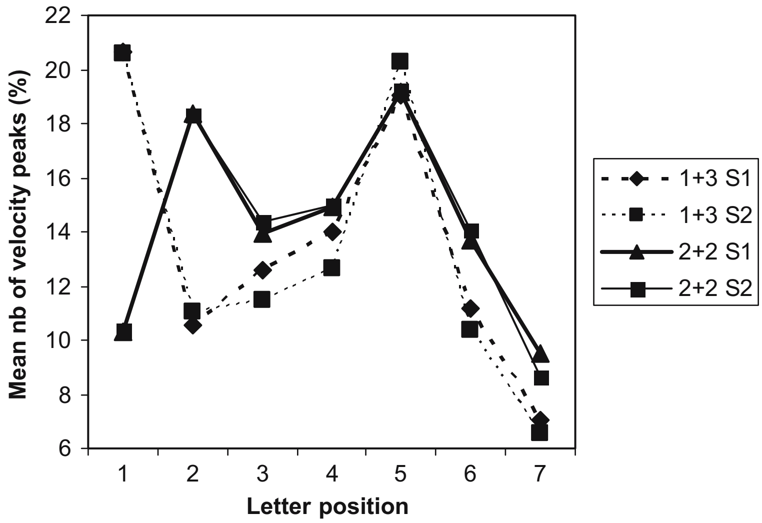

Figure 4. Mean number of velocity peaks per stroke (%) for each letter in 1+3 and 2+2 words during sessions 1 (S1) and 2 (S2).

the ones who had the most dysfluent movements, $r(34) = -0.65$, $P > .05$ in the 1st session, and $r(34) = -0.71$, $P > .05$ in the 2nd session.

Discussion

This experiment examined whether the grapheme structure of words can constrain the organisation of motor processing. As in Experiment 1, duration and dysfluency measures increased at the grapheme and syllable boundaries, in both sessions. For the 2 + 2 words, the results indicate that the children prepared the movement to write the first complex grapheme before movement initiation. The duration and dysfluency peaks at letter 2 are the result of parallel processing of the local parameters to produce letter 2 and the preparation of the second complex grapheme. They then processed the movement to write the second syllable during the production of its first letter. For the 1 + 3 words, movement time and dysfluency were high at letter 1. The children prepared the movement to write the first simple grapheme before starting to write. The duration and dysfluency peaks at letter 1 resulted from the simultaneous processing of the local parameters of letter 1 and the processing of the complex three-letter grapheme. The second peak appeared at letter 5, indicating, as in Kandel and Valdois (in press a), that while processing the local parameters of letter 5, the motor system processes the parameters related to the movements needed to finish writing the syllable. This is confirmed by the fact that duration and dysfluency measures decreased progressively until the end of the word.

Taken together, the results suggest that the children used grapheme and syllable-sized units to organise their handwriting movements. They prepared the first syllable in a grapheme-by-grapheme fashion and then produced the second syllable as a whole unit. As in Experiment 1, there were no major differences between the two sessions. Therefore, once the children have learned the phonological recoding rules, they apply them irrespective of the size of the complex grapheme. This idea is in agreement with the significant correlations between reading performance and movement time and fluency. Moreover, the children mostly adopted an analytic strategy when writing the words.

General discussion

This study examined whether graphemes are used as inputs for motor production during the acquisition of writing skills. In Experiment 1, first graders wrote words varying in the number of graphemes (two and four) and grapheme structure (2 + 2 and 1 + 1 + 1 + 1). In Experiment 2, the initial syllable consisted of two graphemes, but in one condition there were two two-letter complex graphemes (2 + 2), and in the other there was a one-letter grapheme followed by a three-letter grapheme (1 + 3). We analysed the distribution of movement duration and dysfluency throughout the word to evaluate whether there was simultaneous processing of local letter parameters and information on the following grapheme at the grapheme boundaries. The experiments were conducted in two sessions.

The analysis of 2 + 2 words revealed movement time and dysfluency peaks at letters 2 (grapheme boundary) and 5 (second grapheme boundary and syllable boundary). This pattern of duration and dysfluency distribution suggests that the children prepared the movement to produce the first complex grapheme before starting to write. The peaks at letter 2 indicate that the children processed the movement to produce the second complex grapheme in parallel to the calculations of the local parameters needed to write letter 2 (i.e., allograph selection, size calculations and muscular adjustments). The duration and dysfluency peaks at letter 5 show that once the children finished producing the second complex grapheme, they processed the movement to produce the second syllable. They did so while processing the local parameters to write letter 5. The fact that duration and dysfluency values then decreased progressively until the end of the word indicate that the handwriting system processes the whole syllable while producing letter 5. For the 1 + 1 + 1 + 1 words, movement time and fluency were stable throughout the first syllable. This means that the children prepared the movements to write the first syllable letter-by-letter, i.e., grapheme-by-grapheme. The duration and dysfluency peaks at the first letter of the second syllable (letter 5) indicate that the children programmed the gesture to produce the second syllable while writing the first letter, as for the 2 + 2 words. For the 1 + 3 words, the analysis of movement time and dysfluency revealed a peak at letter 1. This suggests parallel processing of the following three-letter complex grapheme and the local parameters to produce letter 1. The fact that duration and dysfluency values remained stable and low in letters 2, 3 and 4 confirm the idea that the children processed the entire complex grapheme while producing letter 1. As with 2 + 2 and 1 + 1 + 1 + 1 words, there was a second peak at letter 5 (i.e., at the first letter of the second syllable). Duration and fluency measures then decreased until the end of the word.

In sum, the duration and dysfluency distributions reveal that the children processed the first syllable of the words grapheme-by-grapheme, irrespective of the number of letters that composed them. The movements to write the first grapheme were prepared before starting to write. They then processed the following graphemes on-line, parallel to the processing of the local parameters needed for letter production (cf. Van Galen, 1991; Van Galen et al., 1986). The peak at the first letter of the second syllable indicates that the children processed the second syllable as a whole unit while producing its first letter. These peaks at the first letter of the second syllable seem to be systematic in French, as shown by Kandel and Valdois (in press a and b). The progressive decrease of duration and dysfluency values towards the end of the word provides further evidence that the children prepared the entire syllable in advance. These results therefore indicate that the grapheme and syllable structure of words determines the timing of the motor production during handwriting. The children prepared the first syllable of the word grapheme-by-grapheme and processed the second syllable as a whole unit while producing its first letter. The fact that movement time and dysfluency measures presented very similar patterns in the two experiments reinforces this idea.

The results show that the children exhibit an anticipatory behaviour, in an adult-like fashion (Van Galen et al., 1986; Van Galen, 1991). The higher-order modules anticipate and process information related to the forthcoming parts of the word while writing a current sequence. In the present experiments, the graphemic and syllabic structure of orthographic representations at the spelling module determined the timing at which the children processed the movements needed to write a word. The results clearly show that the children did not write letter-by-letter but grapheme-by-grapheme and syllable-by-syllable. The fact that the motor system processes the first syllable grapheme-by-grapheme and the second syllable as a whole unit and not grapheme-by-grapheme could be due to anticipatory higher-order processing done before movement initiation and/or during the production of the first syllable. Further research needs to be done to assess this issue. In particular, studies must be done with words of more than two syllables.

It is interesting to point out that there were no differences between the two sessions. This means that the children used grapheme and syllable units as inputs to the motor system from the beginning of the acquisition processes. Once they master phonological recoding skills, they apply the conversion rules systematically, irrespective of the size of the complex graphemes. This idea is supported by the fact that the children mostly adopted an analytic strategy during the task. Furthermore, the significant correlations between reading performance and movement time and fluency indicate that reading and writing skills are extremely linked, as suggested by Sprenger-Charolles et al. (2003). Of course, this kind of reasoning can only be produced in the context of our task, where the spelling of the word was available until the children had finished writing it. In a writing to dictation task, the children would have made many phonologically plausible errors (as **chamvre* instead of *chanvre*) because they do not yet have stable and detailed orthographic representations (Perfetti, 1992). To examine whether the grapheme still plays a major role in motor production when orthographic representations can be accessed directly as whole orthographic units, new experiments should be conducted with older children and adults.

Note

1. We will refer to one-letter graphemes as *simple graphemes* and to graphemes of more than one letter as *complex graphemes*.

Appendix 1

Words used in Experiment 1. The 2 + 2 words have two complex graphemes in the first syllable. The 1 + 1 + 1 + 1 words have four simple graphemes in the first syllable.

2 + 2 words	1 + 1 + 1 + 1 words
chambre	lorsque
chanson	brusque
chanter	cristal
chanvre	brioche
chauvin	fresque
quintal	scruter
chaînon	crisper
guinder	frasque

Appendix 2

Words used in Experiment 2. All the words have two complex graphemes. The 2 + 2 words have two two-letter complex graphemes in the first syllable. The 1 + 3 words have a simple grapheme followed by a three-letter complex grapheme in the first syllable.

2 + 2 words	1 + 3 words
chanson	peintre
chanter	peindre
chanvre	feindre
quintal	geindre
chaînon	teindre
guinder	feinter

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