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How do movements to produce letters become automatic during writing acquisition? Investigating the development of motor anticipation

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Abstract

Learning how to write involves the automation of grapho-motor skills. One of the factors that determine automaticity is *motor anticipation*. This is the ability to write a letter while processing information on how to produce following letters. It is essential for writing fast and smoothly. We investigated how motor anticipation processes build up during the period of handwriting automation. Children aged 8, 9 and 10 years had to write two letters (*ll*, *le*, *ln*) in cursive writing on a digitizer. Motor anticipation referred to processing changes in size (*ll* vs. *le*) and rotation direction (*le* vs. *ln*) of the second letter while writing the *l*. We recorded three measures on the *l* upstroke and downstroke. The movement time data indicate that the *l* upstroke was very variable. The *l*'s downstroke duration was shorter for *ll* than *le* and the latter was in turn shorter than *ln*. This pattern was already observed at age 8. Trajectory length data revealed that the anticipation of a single parameter such as size change is enough to produce a trajectory increase but the addition of parameters is not cumulative, as we observed for stroke duration. The dysfluency data indicated that at age 8, dysfluency values were equivalent for upstrokes and downstrokes. At ages 9 and 10, the children produced more dysfluency on downstrokes than upstrokes. Previous studies on writing with adults have shown that the anticipation of the following letter affects the production of the *l*'s downstroke. The production of the upstroke did not vary. This experiment suggests that learning to anticipate in handwriting production requires: a) rendering the movements to produce the upstroke constant; and b) modulating the downstroke as a function of the spatial characteristics of the following letter. The pattern of movement time data suggest that motor anticipation would start to be adult-like at around age 9. Dysfluency and latency measures do not seem to be very informative about the development of motor anticipation in handwriting.

Keywords

anticipation, automation, children, handwriting, motor production

Writing is one of the basic communication tools in our society. However, there is not much research on how we produce written language. We have even less knowledge about how children acquire writing skills. This is surprising since children spend at least 50% of their school time writing (Tzeng & Chow, 2000). This is even more surprising given the high percentage of writing difficulties children have in their everyday life. A study carried out in Israel with third-graders indicated that 10–30% of the children had difficulties with writing (Rosenblum, Weiss, & Parush, 2004). Another study done in the Netherlands found that 11% of the girls and 21–32% of boys experienced some kind of writing difficulty in elementary school (Smits-Engelsman, Van Galen, & Michels, 1995). The present study was conducted in France. It investigated the development of motor processes. We aimed at understanding how children learn to anticipate forthcoming movements to speed up the writing process. The acceleration of hand gestures is essential for rendering handwriting movements automatic. This allows the child to use cognitive and attentional resources for the other components of writing such as spelling processes, sentence construction and content planning.

Writing is a linguistic movement. It requires high proficiency in the recovery of spelling information and motor control. Thus, learning how to write involves the acquisition of detailed orthographic representations (e.g., Frith, 1986; Share, 1995) and the automation of grapho-motor skills (Mojet, 1991). Children learn word-spelling simultaneously to motor production. At the beginning of the acquisition process, the spelling and motor processes are quite independent from each other because they are both extremely consuming. Before age 8, handwriting movements are rather slow. The letters are "built" stroke by stroke. There are several pauses within and between strokes. This is due to the permanent control and close sensory guidance the child has while he/she produces the movements (Halsband & Lange, 2006). The child is too concentrated in producing letter shapes correctly. This is particularly important when learning cursive handwriting. Articulating the writing gestures to connect one letter to another constitutes a supplementary cognitive load (Thomassen & Schomaker, 1986). This aspect is very relevant for our study because in France, children learn how to write in cursive style. Writing instruction begins formally in Elementary

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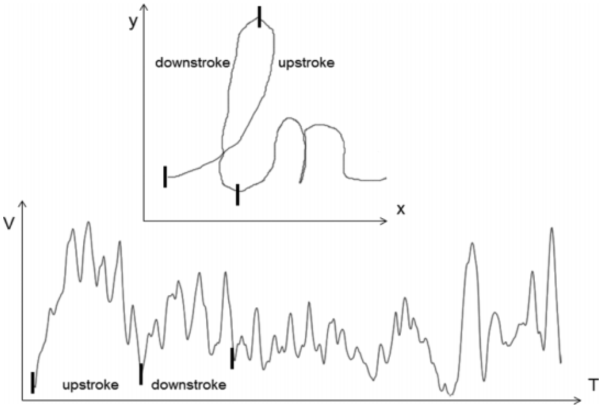

Figure 1. Example of an *ln* production of an 8-year-old boy (top) and its corresponding velocity profile; bottom, V = velocity (cm/s), T = time (ms). The dashes indicate the upstroke and downstroke boundaries. The segmentation on the xy space was done on the basis of the highest (upstroke) and lowest (downstroke) values on the y axis. These points correspond to the velocity minima indicated with dashes in the velocity profile.

Figure 2. Examples of bigrams *ll*, *le* and *ln* in cursive writing. The children saw each bigram on the screen as a stimulus. They were instructed to write the bigram on a lined paper stuck to the digitizer.

School at age 6. In many Pre-Primary schools, however, the children learn how to write some words around age 5.

With practice, the child generates sensory-motor maps and "motor programs" that become progressively more stable (Schmidt, 1988). Motor programs contain information on letter shape as well as stroke order and direction (Meulenbroek & Van Galen, 1989). They are activated from long-term memory each time the child needs to produce a given letter. The consolidation of motor programs requires a long learning process. Writing proficiency consists of the ability to activate the correct sensory-motor maps quickly and effectively. This allows the child to rely less on sensory feedback and more on the information encoded in the motor program. This will decrease the cognitive load for motor control. There will be a significant decrease in writing time. Also, writing movements will become more smooth and continuous; that is, without pauses between the letter's components. The child will therefore have cognitive and attentional resources for the other kinds of processes involved for writing proficiency such as sentence construction and text planning.

Kandel and Perret (in press) conducted an experiment indicating that spelling and motor processes already interact at age 8. At this age the child's sensory-motor maps are stable enough so he/she can deal with spelling recovery and motor production simultaneously. Spelling processes activate word representations before starting to write. They are still active while the child is writing the initial letters of the word. At around 10–11 years of age, writing speed increases considerably and motor production becomes automatic. Van Galen (1993) also found that at this age there is less variability in the children's writing abilities. He explained this in terms of an increase in neuro-motor maturation. So, between the ages of 8 and 11 years, the children's handwriting movements progressively gain in automation. One of the factors that determine automation is *motor anticipation*. This is the ability to write a letter while processing information on how to produce following letters. The parallel processing of the current letter and the following ones has consequences on the kinematic parameters that regulate motor production.

To produce cursive handwriting, we generate continuous sequences of letters varying in shape, size and stroke direction. Previous research reported adult data indicating that the shape and movement time of a letter will be affected by the spatial and motor constraints of the surrounding letters (Thomassen & Schomaker 1986; van Galen, Meulenbroek, & Hylkema 1986). In Orliaguet and Boë (1990), French adults had to write cursive *ll* and *ln* letter sequences on a digitizer. To write *n* in *ln*, we have to recall the motor program of the *n*. We also have to consider that producing *n* after *l* requires a change in stroke size. As can be observed in Figure 1 and Figure 2, *l* is almost double the height of *n*. There is also a change in stroke direction. Producing *n* requires a rotation of the wrist. To write the second *l* of *ll* instead, we just repeat the motor program of the first *l*. Its motor program was already activated for the production of the first *l*, and therefore, it can be accessed immediately. In addition, there are no size or stroke direction changes to be considered with respect to the first *l*. So if motor anticipation occurs simultaneously to the production of the first *l*, writing the *l* of *ll* requires less cognitive resources than the *l* of *ln*.

Orliaguet and Boë (1990) measured the movement time for producing the first *l* to examine whether the processing of size and direction changes affected the production of the first *l*. They split the first *l* into two strokes (Figure 1) to see whether the anticipation of the following letter modulated the movements' first and/or second phase. The first phase concerns the upstroke, which is the upward movement to produce the *l*. The second phase is the downstroke; it concerns the final downward movement. The results revealed that upstroke duration was not affected by the letter following the *l*. It was equivalent for the *l* of *ll* and *ln*. According to the authors, there were no temporal differences because the upstroke movement was programmed before starting to write. Downstroke movement time, however, was longer for the *l* of *ln* than *ll*. The authors interpreted this result in terms of differences in processing load of the second letter. During the production of the *l* downstroke, the participants anticipated changes in size and stroke direction for producing *n*. This requires more processing than just reproducing the motor program of an *l*.

Further research provided evidence indicating that anticipating one parameter change is enough to affect the timing of the *l* downstroke (Boë, Orliaguet, & Belhaj, 1991). The authors compared the duration of the *l* of *ll* and *le* to examine whether a size change would modify the timing of the downstroke. Note that a cursive *e* has the same shape as *l* (see Figure 2); it is just half its height. Boë et al. (1991) found that the *l* downstroke was shorter when the *l* was followed by another *l* than when it was followed by an *e*. They also examined the effects of a change in stroke direction by comparing the movement duration of the *l* of *le* and *ln*. The *l* downstroke duration was shorter when the *l* was followed by *e* than when it was followed by *n*. Upstroke duration was equivalent for the *l* of *ll*, *le* and *ln*. This pattern of results indicated that while we produce the last stroke of a letter—in this case the *l* downstroke—we are also processing the movements we will have to do to produce the following letter. In other words, while we write we anticipate the next letter. This is essential for the proficiency of cursive handwriting and automation.

Motor anticipation speeds up writing by rendering the movements smooth, continuous and fast. This idea is supported by several studies indicating that when someone has severe difficulties in coordinating the components of a motor sequence, like in Parkinson's disease, he/she segments the sequence into simpler elements. This segmentation results in an important increase in movement time and a decrease in speed. When this occurs, the ability to anticipate forthcoming sequences is lost or severely impaired (see Gentilucci & Negrotti, 1999, for an example in grasping sequences). Bidet-Ildei, Pollack, Kandel, Fraix, and Orliaguet (2011) carried out an experiment in which Parkinson's disease patients had to write *lll* and *lln* trigrams on a digitizer. Upstroke and downstroke duration measures of the second *l* did not exhibit any sign of motor anticipation. The productions of matched healthy adults yielded downstroke duration differences. The second *l* of *lll* was shorter than the one in *lln*. The upstroke durations were equivalent. It is noteworthy that under dopaminergic medication or bilateral deep brain stimulation treatments the patients exhibited movement times that were similar to the ones observed for healthy participants. In other words, under treatment, the downstroke of the second *l* of *lln* was longer than in *lll*. The patients could therefore anticipate the third letter during the production of the downstroke of the second one.

Furthermore, an interesting phenomenon of motor anticipation in handwriting is that the temporal differences in the *l* downstroke are detected by the visual system to predict the following letter (Kandel, Orliaguet, & Boë, 1994, 1995, 1997, 2000; Kandel, Orliaguet, & Viviani, 2000). In a series of experiments, the participants saw the movement to produce the *l* on the screen of a computer. The movement stopped at the end of the *l* downstroke. They were able to say whether the next letter was *l*, *e*, or *n*. This indicates that visual processes use anticipatory information to predict the identity of forthcoming motor sequences.

The anticipation of subsequent motor sequences also occurs in other kinds of movements. It is observed in the production of any sequence of actions (e.g. grasping; Louis-Dam, Kandel, & Orliaguet, 2000). When we produce an action, the movements are articulated together to render the whole movement sequence efficient, smooth and fast (cf. Lashley, 1951: serial ordering problem). Motor anticipation requires that we activate information on what we have to do next. Following the rationale presented by van Galen's (1991) handwriting model, motor anticipation results from the simultaneous processing of the local parameters to produce a given letter and the activation of the motor program to produce the following one (see also van Galen et al., 1986). Because cognitive resources are limited, parallel processing will affect the timing of the *l* downstroke. So when motor anticipation occurs, the temporal parameters of a current sequence will be regulated by the constraints of the following letter (Keele, Cohen, & Ivry, 1990).

Motor anticipation has been observed in other linguistic movements. In typing, Gentner, Grudin, and Conway (1980) observed that the finger of the right hand to type *i* in the sequence *an epic* starts more than 100 ms before the movement of another right-hand finger to type *p*. The Activation Triggered Schema proposed by Rumelhart and Norman (1982) accounts for these results by supposing that the hand and fingers are "attracted" to the target positions as a function of their respective activation levels. Thus, hand and fingers would be attracted to the key that has to be typed immediately but *also* to the keys of the following letters. The system anticipates the following typing movements. In speech movements, lip gestures also anticipate the production of the forthcoming sounds (Daniloff & Moll, 1968, in English; Lubker, McAllister, & Carlson, 1974, in Swedish; Benguérel & Cowan, 1974, in French). In the latter study, motor anticipation was observed in /ICy/ sequences (C = consonant cluster) like /ynsinistRstRyktyR/ ("une sinistre structure"). The protrusion of the upper lip to produce the second [y] starts well before its acoustic output. In sum, motor production is serial but the production of a sequence of movements involves the activation of several processes at the same time.

It is likely that children anticipate following sequences in speech very early in life since they speak fluently by the age of 3 (E. Bates, Dale, & Thal, 1995). Coarticulation is smooth and fast. Written language, however, has to be taught explicitly. Writing instruction starts formally at age 6 (at least in France). At the beginning of the acquisition process, the child has to memorize and learn how to produce each letter of the alphabet. Then, there is a long practice period in which the motor programs become progressively more stable. Movement control improves significantly. In France, the children also have to learn how to articulate the grapho-motor movements so that cursive writing is produced efficiently. After systematic practice—and neuro-motor maturation (cf. van Galen, 1993)—the production of writing movements will start to become automatic 2 or 3 years later. Writing will be progressively more continuous, smooth, and fast. This implies that motor anticipation should appear at this period of the acquisition process. The present research aimed at investigating how motor anticipation appears during the development of handwriting skills. We expected it to occur during the period in which handwriting becomes automatic. At this time of the acquisition process writing movements become fast and smooth. We conducted an experiment in which children of ages 8 to 10 had to write *ll*, *le*, and *ln* sequences on a digitizer. We measured the *l* upstroke and downstroke movement time, of course, as in previous adult studies. We also analysed other parameters that are relevant for the understanding of handwriting acquisition such as latency, movement fluency, and trajectory length. Previous developmental data revealed that rotation direction changes in cursive handwriting produce increases in some of these measures (Meulenbroek & van Galen, 1986). Rotation direction changes constitute cognitive loads that are particularly demanding. We predicted that the anticipation of size changes (*ll* vs. *le*) and rotation direction changes (*le* vs. *ln*) would modulate movement time, latency, movement fluency, and trajectory length.

Method

Participants

A total of 66 children participated in the experiment. There were 22 children aged 8 (mean age: 8 years 8 months, $SD = 3.99$) attending third grade, 22 children aged 9 (mean age: 9 years 9 months, $SD = 3.38$) attending fourth grade, and 22 children aged 10 (mean age: 10 years 7 months, $SD = 3.79$) attending fifth grade. They were all right-handed and native French-speakers. They attended an Elementary School in downtown Grenoble. The school year started in September and the experiment was conducted in March. Reading and writing explicit instruction started in the first grade. The

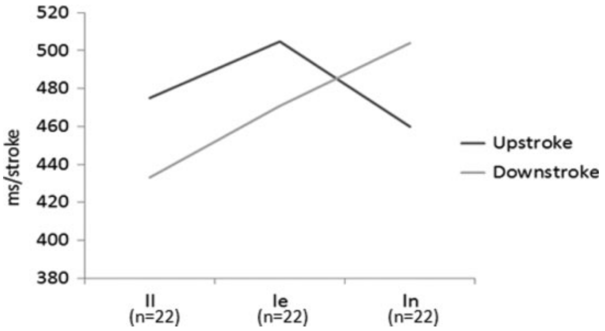

Figure 3. Movement duration values (ms) for upstrokes and downstrokes for each bigram type (*ll*, *le* and *ln*) (n = 66).

children are around 6 years old in first grade. None of the participants were repeating or skipping a grade, and they were attending their grade at the regular age. They had normal or corrected-to-normal vision. The parents and teachers reported no hearing impairments, learning disability, brain, or behavioural problems. School attendance was regular. They participated in the experiment under parental written consent.

Material and procedure

The stimuli were three handwritten bigrams *ll*, *le*, and *ln* written in cursive style (Figure 2).

Stimulus presentation and movement analysis were controlled by *Ductus* (Guinet & Kandel, 2010). The bigram was presented in front of the child, on the centre of the screen of a laptop. An auditory signal and a fixation point (100 ms duration) preceded bigram presentation. The child's task was to write the *ll*, *le* or *ln* bigram on a sheet of paper that was stuck to the digitiser (Wacom Intuos 3 – A5, sampling frequency 200 Hz, accuracy 0.02 mm). The bigram remained on the screen until the child finished writing on it. The digitiser was connected to a laptop that monitored the writing movement. The children had to write the letters as they would have done in class; that is, in cursive handwriting. Since the bigram frequency of the letter sequence is variable in French, we told the children before starting the experiment that they will have to write either *ll*, *le*, or *ln*. According to Content and Radeau's (1988) data base, *ll* has a bigram frequency of 932 in French words' medial position and 34 in final position. Bigram *le* has a bigram frequency of 206 in French words' initial position, 1,087 in medial position and 4,442 in final position. Bigram *ln* has a bigram frequency of 4 in French words' medial position. With this procedure we expected to activate the three bigrams, irrespective of the bigram frequency. The children had to write with a special pen (Intuos Inking Pen) on a lined paper that was stuck to the digitiser. The paper was taken from the type of notebooks the children use to write when they are in school (vertical limit = 0.8 cm, horizontal limit = 17 cm). The children became familiar with the material by writing their name. Two practice items preceded the experiment. We instructed the children to start writing the two letters as soon as they could. There were no time limits or speed constraints during writing. The experimenter clicked on a button to start the following trial. The bigrams were randomised across participants. The children were tested individually in a quiet room inside the school. The experiment lasted 5 to 10 minutes.

Data processing and analysis

There were four measures. Latency referred to the time between bigram presentation and the moment the child started to write (pen pressure > 0). We carried out the other three measures on the upstroke and downstroke of the *l*. To segment the *l*'s into two strokes, we used the highest value on the y axis and the closest tangential velocity minima to determine the end of the upstroke (Figure 1). We used the lowest value on the y axis and the closest tangential velocity minima to determine the end of the downstroke. Stroke duration concerned the time (ms) the children took to write each stroke. The trajectory concerned the path (cm) of the pen for each stroke. Movement fluency concerned the number of absolute velocity peaks in the velocity profile for each stroke (Meulenbroek & van Galen, 1989).

For each analysis, values for which the residuals were larger than twice the standard deviations were considered outliers and removed (Baayen, 2008; Baayen & Milin, 2010). The statistical analyses were performed on latencies, stroke duration, trajectory and movement fluency values. ANOVAs were conducted on the parameters obtained with Hierarchical Linear Model analyses (HLM; Snijder & Bosker, 1999) using the R-software (R version 3.0., package lme4; Bates, Maechler, & Bolker, 2013) with participants as random-effect variable. Three fixed-effects factors were included in the HLM models: Age (8, 9, and 10 years old); Type of bigram (*ll*, *le*, and *ln*); and Stroke (upstroke and downstroke). The latter was not included in the latency analysis. A hierarchical organisation allowed us to take into account the absence of independence of the children's performance across age groups (Musca et al., 2011). The most complex adjustment model (Bar, Levy, & Scheepers, 2013)—that is, adjustment on intercept and on slopes—was included on all models for by-children adjustment. Likelihood-ratio tests were conducted to test the mixed-effects (see Pinheiro & Bates, 2000). For all fixed-effects tests, p values were obtained reporting F values on the Fisher distribution with as error degree of freedom the number of observation minus the number of conditions (n–1 –1). Finally, orthogonal contrasts were used for multiple comparisons. See the Appendix for details on these measures.

Results

Stroke duration

We recorded 396 movement duration values (66 participants × 3 Bigrams × 2 Strokes). 4.80% errors (19) and 4.55% outlier values (18) were excluded from the analyses. None of the mixed-effects reached significance (χ^2s < 1). Bigram type affected stroke duration, $F(2, 358) = 6.73$, $p < .001$. The interaction between Bigram and stroke type was significant, $F(2, 358) = 5.44$, $p < .01$. Figure 3 presents upstroke and downstroke durations for the three bigrams.

Bigram type affected upstroke duration, $F(2, 180) = 3.44$, $p < .05$. The upstroke was longer for the *l* of *le* than *ll*, $F(1, 180) = 5.14$, $p < .05$, and *ln*, $F(1, 180) = 4.49$, $p < .05$. Upstroke durations for *ll* and *ln* were equivalent ($F < 1$). Bigram type also affected downstroke durations, $F(2, 177) = 8.70$, $p < .001$. The downstroke duration was shorter for the *l* of *ll* than the *l* of *le*, $F(1, 177) = 4.38$, $p < .05$, and *ln*, $F(1, 177) = 16.32$, $p < .001$. The *l* downstroke durations of *le* were in turn shorter than *ln*, $F(1, 177) = 3.76$, $p < .05$. All the other main effects and interactions failed to reach significance ($F < 1$).

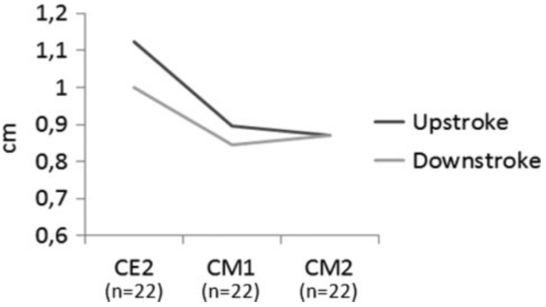

Figure 4. Trajectory length (cm) for upstrokes and downstokes for each age group; 8 ($n = 22$), 9 ($n = 22$) and 10 ($n = 22$).

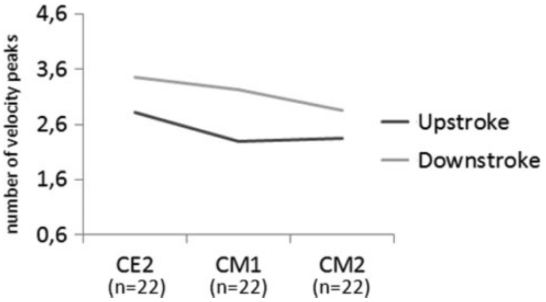

Figure 5. Movement dysfluency values (number of velocity peaks) for upstrokes and downstokes for each age group; 8 ($n = 22$), 9 ($n = 22$) and 10 ($n = 22$).

Trajectory length

We recorded 396 values (66 children × 3 Bigrams × 2 Strokes). The 16 errors (4.04%) and 6 outlier values (1.52%) were excluded from the analyses. None of the mixed-effects reached significance (χ^2s < 1). There was a main effect of Bigram type, $F(2, 373) = 4.06$, $p < .01$. Trajectories for the *l* of *ll* were shorter than for bigrams *le*, $F(1, 373) = 6.24$, $p < .01$, and *ln*, $F(1, 373) = 10.19$, $p < .001$. Stroke trajectories for *le* and *ln* were equivalent ($F < 1$). Upstrokes were longer than downstrokes, $F(1, 373) = 4.22$, $p < .05$. The analysis also yielded a main effect of age, $F(2, 373) = 4.72$, $p < .01$. The trajectories were longer for 8-year-olds than 9-year-olds, $F(1, 373) = 3.95$, $p < .05$, and 10-year-olds, $F(1, 373) = 4.16$, $p < .05$. The difference between 9- and 10-year-olds did not reach significance ($F < 1$). The interaction between Age and stroke type was significant, $F(2, 373) = 6.44$, $p < .01$. Figure 4 presents the trajectory length for upstrokes and downstrokes for each age group.

Upstroke trajectory was longer for the 8-year-olds than the older children (age 9: $F(1, 186) = 4.79$, $p < .05$; age 10: $F(1, 186) = 8.27$, $p < .01$). There was no difference between 9- and 10-year-olds ($F < 1$). The trajectories did not differ across age for downstrokes ($F < 1$).

Movement dysfluency

We recorded 396 dysfluency values (66 participants × 3 Bigrams × 2 Strokes). 3.54% errors (14) and 4.55% outlier values (18) were excluded from the analyses. None of the mixed-effects reached significance (χ^2s < 1). We observed more movement dysfluency for downstrokes than upstrokes, $F(1, 363) = 20.49$, $p < .001$. Moreover, this effect was modulated par age, $F(2, 363) = 3.40$, $p < .05$. Figure 5 presents the movement dysfluency values for upstrokes and downstrokes for each age group.

Movement dysfluency for upstrokes and downstrokes was equivalent for 8-year-olds, $t(112) = -1.03$, $p = .15$. For the older children, downstrokes produced more dysfluency than upstrokes (9-year-olds: $t(122) = -4.26$, $p < .001$; 10-year-olds, $t(126) = -2.70$, $p < .01$).

Latency

We recorded 198 latency values (66 children × 3 Bigrams). 25 errors (12.62%) and 6 outlier values (3.03%) were excluded from the analyses. None of the mixed-effects reached significance (χ^2s < 1). The Bigram factor yielded significant effects, $F(2, 171) = 10.60$, $p < .001$. Table 1 presents the latency values for the three bigrams for each age group.

Orthogonal contrasts revealed that all the children took longer to start writing *le* than *ll*, $F(1, 171) = 15.70$, $p < .001$, and *ln*, $F(1, 171) = 13.94$, $p < .001$. The latencies for *ln* were numerically higher than *ll* but the differences did not reach statistical significance ($F < 1$). All the other main effects and interactions failed to reach significance ($F < 1$).

Discussion

Motor anticipation is an essential component for automation in handwriting skills. This research investigated the processing of motor anticipation during the period in which writing movements start to become automatic. Children of ages 8 to 10 wrote *ll*, *le* and *ln* bigrams in cursive writing on a digitizer. We examined the production of the *l*'s upstroke and downstroke. The analysis revealed that bigram type affected stroke duration. The *l* upstroke durations yielded a *le* > *ll* ≈ *ln* pattern. For downstrokes, the durations yielded a *ll* < *le* < *ln* pattern. Bigram type also affected trajectory length, with a *ll* < *le* ≈ *ln* pattern. Bigram type did not affect movement fluency. Dysfluency for upstrokes and downstrokes was equivalent for 8-year-olds. For the older children, downstrokes produced more dysfluency than upstrokes. Upstroke/downstroke trajectory length and movement dysfluency were mainly modulated by age but not by bigram type. Globally, trajectory and dysfluency decreased from ages 8 to 9 and remained stable from ages 9 to 10. Latency values revealed that all the children took longer to initiate the movement to produce *le* than *ll* and *ln*.

The results on stroke duration constitute the most important contribution to the understanding of motor anticipation development in handwriting. Upstroke duration for the *l* of *le* was longer than *ll* and *ln*; the latter yielded equivalent movement times. The *l* downstroke data indicated that durations were shorter for *ll* than *le*, and in turn shorter than *ln*. The *l* downstroke durations increased as the spatial parameters to anticipate increased: *ll* < *le* (size change) and *le* < *ln* (direction change). This is evidence for motor anticipation. The downstroke movement time pattern is the same as the downstroke duration pattern observed with adults (Boë et al., 1991). In adults, the *l* upstroke durations were equivalent for the three bigrams whereas the downstroke durations varied as the spatial constraints of the following letter increased. So the differences in trend between children and adult durations were mainly observed for the upstroke. Upstroke durations were variable in children but not in adults. This suggests that motor anticipation is already present at

Table 1. Mean latency values (ms) and the corresponding standard deviations (in brackets) for bigrams *ll*, *le*, *ln* for each age group ($n = 66$).

	8-year-olds ($n = 22$)	9-year-olds ($n = 22$)	10-year-olds ($n = 22$)
ll	1,749 (397)	1,646 (341)	1,502 (379)
le	1,864 (411)	1,801 (337)	1,832 (381)
ln	1,791 (291)	1,617 (296)	1,601 (381)

age 8 but the regulation of upstroke duration is still in the process of being accomplished.

It is important to point out that the relevant point of motor anticipation here is the *pattern* of results and not absolute duration. Adults write faster than children. Stroke duration for adult spontaneous cursive handwriting at "normal size" (≈ 1 cm) is generally around 100 ms (see Thomassen & Teulings, 1985). We observed mean stroke durations of 536 ms for the children of age 8, 466 ms for the children of age 9, and 416 ms for the children of age 10. The *l*s had a maximum height of 0.8 cm. The children's strokes can be even longer. Meulenbroek and van Galen (1986), for example, reported that 8-year-olds produced 2-cm loops (that looked like *l*s) in 778 ms/stroke. This means that motor anticipation processing can be functional at age 8 but writing speed has to be increased considerably to attaint adult-like performance. In our study as well as in Meulenbroek and van Galen (1986), the children had to copy the letters. This could have slowed the children's writing movements and yield longer durations than in spontaneous writing. So adult-like writing should be fully achieved when the children are able to a) produce similar upstroke durations; b) regulate the timing of downstrokes as a function of the parameters required for the production of the following letter; and c) decrease movement time.

Another issue on movement duration that deserves some discussion concerns the relationship between motor anticipation and the isochrony principle. Isochrony refers to the observation that writing movement time remains constant despite letter size changes (adults: Viviani & Terzuolo, 1983; children: Meulenbroek & van Galen, 1986). This holds for "normal" writing sizes, between 2.5 and 10 mm (Thomassen & Teulings, 1985), which correspond to the productions the children did in the present research. This means that the durations of all the *l*s should be similar. We observed instead that movement time *does* vary. The timing depends on the anticipation of forthcoming letters. Are isochrony and anticipation principles incompatible? Other studies must be done to examine this issue. The experiments investigating the isochrony principle in handwriting were always done with one letter or sequence. They did not consider contextual effects. However, the anticipation phenomenon is intrinsically linked to the processing of more than one letter (i.e., $l + e$ and $l + n$). Therefore, it is difficult to interpret movement time invariance in the framework of motor anticipation.

The data on trajectory length revealed that trajectories for the *l* upstroke and downstroke of *ll* were shorter than in bigrams *le* and *ln*. These differences could also be due to motor anticipation. When producing the *l* of *ll*, the children repeat the same motor program for the second letter. The child just has to activate the motor program for one letter. When producing the *l* of *le* and *ln* instead, the local parameters of the following letter ($e =$ change in size and $n =$ change in size and direction) have to be considered. In addition, for *le* and *ln*, the child has to activate the motor programs for two letters (i.e., $l + e$ and $l + n$), which should require a stronger cognitive load. The trajectories were longer for the children of age 8 than the older children. These differences were only observed for upstrokes. The 9- and 10-year-olds produced equivalent trajectories. This suggests that trajectory control becomes stable at ages 9–10.

We also measured movement fluency to examine whether motor anticipation would affect the smoothness of the children's writing movements. The data only revealed that movements were more dysfluent for downstrokes than upstrokes, especially for the older children. This is in line with the idea that the anticipation of subsequent motor sequences is essentially done during downstroke production. Further research is required to understand whether motor anticipation really affects movement fluency. Finally, the latency data revealed that the children took longer to start writing *le* than *ll* and *ln*. We have no satisfactory explanation for this.

In summary, the results for movement duration provide evidence for motor anticipation in the downstroke of the *l*. The *l* downstroke movement time is shorter for *ll* than *le* and in turn longer than *ln*. This pattern of results is consistent with previous adult data (Boë et al., 1991; Orliaguet & Boë, 1990). The trend was already observed at age 8. What renders the children's handwriting more adult-like is the regulation of the movement to produce the upstroke and a decrease in movement time. Trajectory length revealed that the anticipation of a single parameter, such as size change from one letter to another, is enough to produce a trajectory increase but the addition of parameters is not cumulative, as we observed for stroke duration. Movement fluency and latencies do not seem to be very sensitive to motor anticipation phenomena. Lastly, the trajectory length and movement fluency data indicated that the children's handwriting becomes "stable" and therefore more automatic at ages 9–10. We observed important trajectory and dysfluency decreases from ages 8 to 9, but no differences from 9 to 10. This is in agreement with previous studies indicating that handwriting production starts becoming automatic around age 9 (Kandel & Perret, in press; Mojet, 1991).

The present research provides data on how the children learn to anticipate forthcoming letters in a smooth and continuous way. We need to anticipate what is going to happen next so we can adapt our movements in an efficient way (van Galen, 1991). At the beginning of the writing acquisition period the child produces the letters of a word in a letter-by-letter fashion. In other words, the motor sequence to produce the word is segmented into its elementary units. The child will activate the motor program to produce the following letters once he/she has finished writing the previous one. This happens because the cognitive, motor and attentional load to write each letter is extremely high (Halsband & Lange, 2006). With practice and neuro-motor maturation, he/she will be able to build more complex letter sequences (van Galen, 1993). The results of the present study suggest that when writing movements start to become automatic, the children will be able to produce a letter and process simultaneously information on the following sequences. This will essentially affect movement duration. Motor anticipation will first regulate downstroke movement time. With practice, the timing to produce upstrokes will become similar.

Further research should be done with children under the age of 8 to examine how motor anticipation emerges during handwriting acquisition. In addition, future studies should consider using other measures that could be more sensitive to motor anticipation patterns. For example, pen pressure, which is a well-established indicator of cognitive and attentional load in handwriting production (Kao, Mak & Lam, 1986), could give more insight into the processes that lead to the automation of handwriting and the stabilization of anticipatory strategies in movement production.

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Appendix: Details for the movement time, trajectory length and movement dysfluency measures

Movement time (ms)

Bigram	Stroke	Age 8	Age 9	Age 10
ll	Upstroke	550	425	462
	Downstroke	470	453	365
le	Upstroke	567	485	493
	Downstroke	517	481	372
ln	Upstroke	529	438	399
	Downstroke	580	513	405

Trajectory length (cm)

Bigram	Stroke	Age 8	Age 9	Age 10
ll	Upstroke	1.08	.87	.83
	Downstroke	.97	.82	.82
le	Upstroke	1.03	.86	.86
	Downstroke	.99	.87	.85
ln	Upstroke	1.16	.89	.81
	Downstroke	1.04	.82	.88

Movement dysfluency (number of velocity peaks)

Bigram	Stroke	Age 8	Age 9	Age 10
ll	Upstroke	2.84	2.14	2.62
	Downstroke	3.09	2.85	2.5
le	Upstroke	2.94	2.71	2.43
	Downstroke	2.75	3.7	2.95
ln	Upstroke	2.71	2.00	2.00
	Downstroke	3.79	3.81	3.14