

## Handwriting isolated cursive letters in young children: Effect of the visual trace deletion

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**Abstract**

This study assesses the handwriting of isolated cursive letters in five-year-old children and the effect of a modification in visual feedback. Sixty-four children copied twelve cursive letters with an inking pen and a non-inking pen. Reducing visual feedback decreased the mean number of penlifts, and increased mean velocity and fluency. However, it increased the size of the letters (trajectory length) and reduced their quality. We suggest that processing visual feedback of the emerging visual trace may interrupt the fluency of the movement, while writing without seeing the trace may place greater emphasis on motor control and the use of somatosensory feedback. This study supplies reflection about sensory feedback and the moment when it should be provided in handwriting instruction. Practitioners should be aware that variation in the writing environment (surface, tools...) modifies sensory feedback and affects handwriting learning (gesture and outcome) in different manner.

**Keywords:** Handwriting, Visual feedback, Children

## 1. Introduction

Handwriting is a complex skill that requires training and many hours of practice to be mastered (Hoy et al., 2011). This motor activity is governed by spatio-temporal rules (Goodnow & Levine, 1973; Lacquaniti et al., 1983): strokes are produced following a specific order; the duration of the movement remains invariant irrespective of its size (isochrony); and the velocity is not constant during the drawing of a letter but depends on the curvature of the trajectory (velocity decreases with curvature in a specific manner defined by the  $2/3$  power law which applies to all biological motion). Isochrony governs the handwriting process even in young children (Pagliarini et al., 2017) whereas the  $2/3$  power law in the context of handwriting is not functional before the age of thirteen (Viviani & Schneider, 1991).

While formal handwriting instruction usually begins in first grade, in some countries, as is the case in France, the recognition of letters and the motor gestures needed to produce isolated cursive letters are learned in kindergarten. Therefore it is important to study the way children produce their first handwriting gestures and to propose early efficient instruction. The present study focuses on the handwriting of isolated cursive letters during the early beginning of handwriting acquisition in 5-year-old children in two conditions: normal writing, and writing with reduced visual feedback.

### 1.1. Handwriting control and role of feedback

Skilled handwriting is monitored by two global modes of control: a predictive feedforward control, that needs an internal representation of action, sometimes referred to as a motor program (Summers & Anson, 2009), and a reactive control where sensory feedback is used to update the ongoing movement (Wolpert et al., 1995; 2011). Two complementary sources of sensory feedback are available to monitor the handwriting gesture: visual feedback and somatosensory feedback (Danna & Velay, 2015). The somatosensory feedback, that comes from proprioception, kinesthesia and tactile perception (Bodegard et al., 2003),

informs about the spatial (trajectory and trajectory length), kinematic (velocity, fluency) and dynamic (pressure) characteristics of handwriting movements. Vision is used to monitor the spatial features of handwriting and the size of letters (Marquardt et al., 1999; Tucha et al., 2008). Visual checking allows precise location of the pen on the writing surface which is necessary to produce joins between letters in cursive handwriting and to control the spacing between words and between letters in manuscript handwriting. The lack of vision particularly impairs the production of letters that require pointing movements (Smyth & Silvers, 1987) since these movements (which can be considered as target reaching movements) require an estimation of the position of the hand during the movement, in order to adapt the previously initiated movement towards the final position of the target. This estimation relies heavily on visual information (Saunders & Knill, 2005).

The two sources of sensory information are complementary (Hepp-Reymond et al., 2009). In the absence of vision, the system can simulate the movement dynamic by using a forward model and can rely on proprioceptive information to estimate the current location of the hand (Wolpert et al., 1995). Studies that modified the availability of visual feedback showed that children tend to increase trajectory length, pressure and velocity when they do not have complete visual information (Chartrel & Vinter, 2006). Modifying the temporal constraint when writing (increasing the speed) had the same kind of effect by decreasing visual control (Chartrel & Vinter, 2008). The increase in size, which maximizes kinesthetic feedback (Clark & Horch, 1986), has been observed in children, adults and Parkinson's disease (Chartrel & Vinter, 2006; Potgieser et al., 2015; van Doorn & Keuss, 1992). Pressure, which reflects an increase in muscle contraction on the pen, may increase the amount of somatosensory information (Levine et al., 1987). Guilbert et al. (2019) showed an interaction between visual and proprioceptive feedback when writing on a tablet screen. Second and fifth graders and adults wrote letters in four conditions: with or without visual feedback (hand and

paper non-visible) on a high or low friction surface. Velocity and size increased in the absence of vision and when participants wrote on a low friction surface. Children were more sensitive to the disruption of feedback than adults and tried more to compensate the absence of one source of feedback (visual or proprioceptive) by increasing the use of the source still available.

### *1.2. Sensory-motor integration and development of motor control*

Before the age of 6, young children tend to produce aiming movements and to draw strokes in a ballistic manner with a very low control of vision (Kao et al., 1986). Visual checking only occurs at the end of the movement (Hay, 1979). Learning novel characters in handwriting, which requires producing small continuous patterns, encourages them to change their strategy and to use visual input more. As shown by Fears and Lockman (2018), copying unfamiliar characters involves more visual fixations than when copying familiar symbols. Thus children aged 6-7 years, who have not yet memorized the motor patterns, tend to rely heavily on visual feedback. As a result, their handwriting is relatively slow, with strong pressure on the pen, large letters and numerous pauses (Accardo et al., 2013; Meulenbroek & van Galen, 1988; Paz-Villagran et al., 2014).

When beginning to learn how to write letters, children follow the instructions of the teacher and try to reproduce a model of the letter with respect to its visual shape, the sequentiality of strokes, and the trajectory. Children progressively integrate sensory-motor information that links the sensory input, the motor input and the result (Wolpert et al., 1995). Knowledge of the result produced by the movement is used to modify the next movement attempt (Schmidt & Lee, 2005). The integration of sensory-motor information helps to slowly build the motor program, that goes from strokes to whole letters (S  raphin Thibon et al., 2018). Through comparison with the model from external feedback provided by the teacher or through the child's self-assessment of the deviation of their production from the norm, the best

sensory motor link can be selected and the motor program eventually becomes stable and allows automation. Séraphin Thibon et al. (2018) observed that before 8 years the motor programs are gradually installed and between 8 and 10 years handwriting starts to become automatized.

The mapping between sensory information and motor command requires attention and working memory resources (Halsband & Lange, 2006). Before 8 years, the integration of the different sources of sensory information is difficult and signals are mostly processed independently (Gori et al., 2008). In the early explicit stage of motor learning, constraints on working memory are high because children need to process a large amount of information such as sensory information about the visual trace, somatosensory information about the motor movement, and verbal instruction (Maxwell et al., 2003).

### *1.3. Letter complexity and learning*

Cursive handwriting is characterized by joined letters, continuous and rotating movements and few penlifts, and thus is very demanding in terms of fine motor skills and is relatively slow (Bara & Morin, 2013; Meulenbroek & van Galen, 1986). When children learn to handwrite letters, they need to change their preferred clockwise direction of rotation of the circles (spontaneously implemented in drawing) to integrate a predominantly counter-clockwise direction of rotation (Meulenbroek et al., 1993; letters <a>, <d>, <o> for instance). Inversions of direction (e.g. letters <g>, <k>, <v>) require a certain degree of motor maturation to be achieved (Feder et al., 2007). Letters do not have the same level of learning difficulty because of various characteristics (e.g. pointing and rotating movements, inversions of direction, sequence of numerous strokes). The presence of pointing movements modifies the kinematic of handwriting: the duration of the movement on the writing surface is reduced to compensate for the additional time induced by the in-air period (Séraphin Thibon et al.,

2019). These pointing movements, which strongly characterize manuscript (Graham et al. 1998) are also found in cursive writing (letters <i> and <t> for instance).

Meulenbroek and van Galen (1986) showed that the most difficult cursive form for primary school children was the wave, which needs a continuous changing movement of wrist and finger. Using a measure of handwriting velocity, Meulenbroek and van Galen (1990) ranked cursive letters according to their level of complexity. The most complex letters were <r> and <z>, which are the only ones to contain horizontally oriented wave form segments. Letters with extenders (e.g. <d>) were more easily written than corpus sized letters (e.g. <a>) probably because a long trajectory induces a faster movement. Writing movements to produce curved lines are less fluent than writing movements for straight lines (S  raphin Thibon et al., 2019). Letter complexity might also be the consequence of the number of strokes. As young children produce letters as a succession of strokes, the cognitive load increases as a function of the number of strokes in the letter (S  raphin Thibon et al., 2018).

### *1.4. The present study*

While a number of studies exist on motor control and the use of feedback in adults' and children's handwriting (for a review, Danna & Velay, 2015), very few of them concern kindergarten children (except Chartrel & Vinter, 2008). Even if some studies have proposed a modification in somatosensory feedback to teach handwriting (e.g. writing in the air, Bara & Bonneton-Botte, 2017; writing with the finger, Patchan & Puranick, 2016), little is known about the effect of these modifications on the different characteristics of handwriting. Kindergarten teachers report that they sometimes modify feedback by asking pupils to write in sand, in the air, or without ink (Bonneton-Botte et al., 2019) but they lack justifications based on research to do so. The increasing use of digital devices facilitates these feedback modifications by adding visual or verbal information, by removing the trace, or deleting the result. While their efficiency has been proved (Patchan & Puranik, 2016; Bonneton-Bott   et



al., 2020), we do not know the exact cause of the improvement. As visual feedback may be easily modified during handwriting teaching and learning we need to know what characteristics of handwriting it could affect.

Two aspects in letter handwriting attest proficiency: the quality of the shape (product) and the quality of the gesture (process) (Rosenblum, Weiss, & Parush, 2003). The quality of the shape refers to the consistent size and legibility of letters whereas the quality of the process involves several dynamic aspects of the gesture (pauses, velocity, fluency). Teachers' methods of instruction and reported practices tend to focus more on the quality of the outcome than on the process (Bonneton-Botté et al., 2019). Because of the constraints in working memory, managing concomitantly all the activities required to write is a source of difficulty (Maxwell et al., 2003). At the initial stage of letter learning, when internal models are under development, learning to write a letter requires substantial cognitive involvement as the child has to process sensory information at the same time as they have to control the gesture. We assume that the more the child focuses on the shape, the more they will rely on visual information, perhaps to the detriment of speed of execution and quality of movement. Processing visual feedback on the letter shape may interrupt the fluency of the movement while writing without seeing the ongoing visual output may place greater emphasis on motor control.

This study has two main objectives: to describe the process and product of young children's isolated cursive letter handwriting, in the initial stages of handwriting acquisition; and to assess the effect of reducing visual feedback by deleting the trace produced by the children in a copying task. A non-inking pen was used to delete the visual trace while preserving the vision of the pen and the hand, and of spatial cues (position on the page). Concerning the description of cursive handwriting we expect to find high velocity but low fluency when young children produce letters (in comparison to older children, Séraphin

Thibon et al., 2018), and differences between the letters depending on their motor complexity (Meulenbroek & van Galen, 1990). Concerning the effect of the writing condition, we assume that the reduction in visual feedback will have a similar effect in kindergarten children to its effect in primary school children by increasing velocity, fluency and trajectory length (Chartrel & Vinter, 2006; Guilbert et al., 2019). As children are not yet familiar with the letters and cannot rely on fully working motor programs, we expect a decrease in the quality of the shape.

## 2. Method

### 2.1. Participants

Sixty-four right-handed children (29 girls and 35 boys), from three different French schools, in the last year of kindergarten participated in the study. Their mean age was 5 years and 6 months. All the children had normal development, with no suspicion of cognitive, visual or behavioral disorder (on the basis of information collected from parents and teachers).

The schools were located in a medium-sized city and were attended by children from a middle socio-economic status. The data were collected at the end of the school year, in April. Cursive handwriting instruction in class had started 4 months before the test. In each, children performed handwriting training sessions with their teacher once or twice a week during 20 minutes to practice writing isolated cursive letters. The exercises consisted in copying a static model of the letters. The three schools followed the same progression in the teaching of handwriting. The letters were drawn on white paper with different tools (pencil, colored pencil, felt-tip pen, brush). The letters were taught as a function of their shape (groups of letters that contain a circle, loop, straight line...). Training was informal, no specific correction or strict instruction for letter handwriting were given. The sessions were considered as a first discovery of the letter shape and the beginning of gesture practice.

This study was conducted in accordance with local guidelines on ethical respect for research with human subjects. The study was approved by the school's inspector, director and teachers. The parents completed a written consent form for each child.

### 2.2. *Material*

A Wacom digitizer tablet covered by a white sheet of paper (A4) was used as the support of writing activities and to collect the data. Two kinds of pen were used: an Intuos inking pen and a non-inking pen.

Twelve letters of the alphabet (<a>, <i>, <r>, <b>, <f>, <m>, <d>, <n>, <t>, <v>, <l>, <p>) were chosen. Except for <f> and <v> (which had never been practiced in class), these letters are frequently proposed by preschool teachers at the beginning of instruction. The selected letters vary in terms of the projection axis, aperture, trajectory length, and direction. They have different levels of motor complexity: wave (<m>, <v>, <n>), loops (<l>, <b>), extenders (<d>, <t>, <p>), inversions (<v>), rotation (<a>, <d>) (Meulenbroek & van Galen, 1990), pointing movements (<t>, <i>) (S  raphin Thibon et al., 2019) and different numbers of strokes (<l>, <m>) (S  raphin Thibon et al., 2018). The model of the letter was in cursive handwriting (which is the usual type of script taught in French schools).

### 2.3. *Procedure*

The children were tested individually. They copied each letter in cursive script once on a white sheet of paper fixed on the tablet surface. The letters were presented in a random order across participants. There were no time limits or speed constraints during writing. The model remained visible until the child had finished writing the letter.

Each child participated in two handwriting conditions:

- with visual feedback: the child used an inking pen to write the letters;
- with reduced visual feedback: the child used a non-inking pen (with a plastic tip): the child could see their hand producing the movement but no trace remained visible. We partially

reduced the visual feedback by deleting the visual trace but preserved the sight of the pen, of the hand, and of some spatial cues (position on the page) to let the writer focus on the movement.

The conditions were counterbalanced between participants. Children were administered the second condition one week after the first. The children were told that one pen used invisible ink and that they had to trace the letter with the correct shape. Two letters (<e> and <h>) were used for training before the children began the task in order to let them test the pen and understand the task. These two letters were not analyzed. For these two letters the result of the handwriting with no ink was shown on the computer so that the children understood that the way they drew the letter was registered and mattered.

As handwriting quality depends on the availability of the internal visual template of the letters, we assessed letter recognition. The experimenter said the name of a letter, and the child had to identify it among 10 other letters by pointing to it with their finger. The nine other letters were visually similar to the target letter. Each correct answer was scored 1. The percentage of children that recognized each letter is presented in table 1.

### *2.4. Assessment of letter handwriting product and process*

Ductus software (Guinet & Kandel, 2010) was used to collect the handwriting data and to calculate trajectory length, velocity, fluency, and in-air periods and their duration. These spatial and kinematic data are usually used to assess handwriting proficiency (Danna, Paz-Villagran & Velay, 2013). A filter with a 12-Hz cutoff frequency was applied on the data.

Trajectory length (cm) refers to the length of the pen tip path on the surface of the digitizer to produce the letter. Velocity refers to the ratio between the trajectory and time (cm/s). Penlifts (in-air periods) correspond to the moments during the writing of one letter when the stylus is not in contact with the surface. The duration of penlifts (milliseconds) corresponds to the ratio between the number of penlifts and their total duration. Fluency

represents fluctuation in the velocity profile (acceleration of the pen). It was measured by the number of inversions of velocity, which was obtained by adding maximum and minimum velocity values. In skilled writing, the fluency measure does not allow comparison between letters because it depends on the number of strokes the letter contains and is relative to the changes in the curvature trajectory. To obtain a measure that is less fluctuating with respect to the letters, we calculated the ratio between the number of inversions of velocity and the number of expected strokes for each letter (as found in Séraphin Thibon et al. (2018)'s study). On the figures, the letters have been arranged according to the number of strokes they contain.

The global stroke order was rated, with one point being awarded for each letter written with the conventional stroke direction.

The global quality of handwriting was judged by two teachers (who were not the teachers of the class that participated in the study), who marked each letter from 0 (unrecognizable) to 5 (perfectly handwritten for a child of that age). The production of each child in the reduced feedback condition was recorded on the computer and then printed on paper to be assessed by the teachers. The child's productions from the two experimental conditions were presented in a random order (subject/condition/letter). The teacher was given no information about who produced the letter or the experimental condition in which it was produced. Each of them marked all the letters produced by the children. The interrater agreement was high (Cohen's weighted kappa coefficient,  $\kappa = .76$ ).

### 2.5. Data Analysis

A multivariate analysis of variance with repeated measures was performed. Two within-subjects factors were considered: Letters (12 modalities) and Condition (2 modalities: normal and reduced visual feedback). *SPSS software was used to perform the statistical analyses.*

## 3. Results

### 3.1. Trajectory length

The effect of Letter ( $F(11,53)=48.33$   $p<.001$  with a large effect size  $\eta^2=.68$ ) and of Condition ( $F(11,63)=75.24$ ,  $p<.001$  with a large effect size  $\eta^2=.54$ ) were significant. When visual feedback was reduced, the trajectory length increased ( $M=3.59$ ;  $SD=0.14$ ) in comparison with the normal writing condition ( $M=2.74$ ;  $SD=0.10$ ). The effect of interaction was significant ( $F(11,53)=5.15$ ,  $p<.001$  with a large effect size  $\eta^2=.13$ ). Bonferroni post hoc analyses revealed that the difference between the two conditions was significant for all letters ( $p<.05$ ). However this difference was more or less large depending on the letter; for example <f> and <m> exhibited a large difference between the two writing conditions (see Fig. 1).

## 3.2. Mean velocity

The analysis revealed a significant effect of Letter ( $F(11,53)=7.49$ ,  $p<.001$ , with a large effect size  $\eta^2=.22$ ) and of Condition ( $F(11,63)=118.76$ ,  $p<.001$  with a large effect size  $\eta^2=.65$ ). The interaction was significant ( $F(11,53)=15.69$ ,  $p<.001$ , with a large effect size  $\eta^2=.34$ ). When visual feedback was reduced, mean velocity improved ( $M=2.86$ ;  $SD=0.14$ ) in comparison with the normal writing condition ( $M=1.72$ ;  $SD=0.08$ ). Bonferroni post hoc analyses revealed that the difference between the two conditions was significant for all letters ( $p<.05$ ). However, this difference was more or less large depending on the letter: for example, <l> and <a> exhibited a marked difference between the conditions (see Fig. 2). Whatever the condition, the letters <l> and <d> differed significantly from all the other letters and were drawn with the highest velocity. Letter <r> differed from the others and was drawn with a significantly lower velocity than <a>, <i>, <l>, <t>, <p> and <d>. The letter <v> was drawn with a lower velocity than <a>, <l>, <t>, and <d> (Bonferroni post-hoc analyses,  $p<.01$ ). The other letters did not differ significantly from each other (Bonferroni post-hoc analyses,  $p<.01$ ).

## 3.3. Fluency (number of velocity inversions/number of expected strokes)

The effect of Letter ( $F(11,53)= 17.35, p<.001$  with a large effect size  $\eta^2=.38$ ) and the effect of Condition ( $F(11,63)=105, p<.001$  with a large effect size  $\eta^2=.62$ ) were significant. The interaction was significant ( $F(11,53)=5.84, p<.001$  with a large effect size  $\eta^2=.13$ ). When visual feedback was reduced, fluency decreased ( $M=4.76, SD=0.2$ ) in comparison with the normal writing condition ( $M=7.1, SD=0.35$ ). Bonferroni post hoc analyses revealed that the difference between the two conditions was significant for all letters ( $p<.05$ ). However, the difference was more or less large depending on the letter. This difference was particularly pronounced for <f> (see Fig.3). Whatever the condition, the letter <f> differed significantly from all the other letters and was the least fluent. The letters <m>, <i> and <t> were more fluent than the other letters. (Bonferroni post-hoc analyses,  $p<.05$ ). The other letters did not differ significantly from each other.

## 3.4. Number of penlifts and mean duration (ms)

Concerning the number of penlifts, the analysis showed a significant effect of Letter ( $F(11,53)=122.35, p<.001$ , with a large effect size  $\eta^2=.59$ ), and of Condition ( $F(11,63)=12.89, p<.001$ , with a large effect size  $\eta^2=.17$ ). The effect of interaction was not significant. When visual feedback was reduced, children made fewer penlifts when writing a letter ( $M=0.39; SD=0.02$ ) than in the normal writing condition ( $M=0.46; SD=0.03$ ). In the normal writing condition some letters were written with no penlifts, except by two or three children (<l>, <r> and <v>), whereas other letters requiring some penlifts (<t> and <i>) were written with respectively 1.18 and 1.12 penlifts on average.

Concerning the duration of penlifts, a significant effect of Letter ( $F(11,53)= 51.04, p<.001$ , with a large effect size  $\eta^2=.91$ ), and of Condition ( $F(11,63)=11.48, p<.001$ , with a large effect size  $\eta^2=.15$ ) was found. The effect of interaction was not significant. When penlifts occurred, their duration was longer in the normal writing condition ( $M=406.07; SD=272.8$ ) than when visual feedback was reduced ( $M=307.21; SD=187.9$ ).

The mean number of penlifts and their duration are presented in table 2.

## 3.5. Stroke order

A paired-sample t-test was performed on the number of letters written with the conventional stroke order. It revealed a significant effect of the writing condition ( $t(63)=-3.54, p<.001$ ). The mean number of letters written with the conventional stroke order was significantly higher with reduced visual feedback ( $M=9.69, SD=1.85$ ) than in the normal writing condition ( $M=9.09, SD=2.24$ ). In the normal writing condition around 90% of the children were able to write <r>, <l>, <n>, <v>, <b> and <m> with the conventional stroke order. Around 70% of the children wrote <a> and <i> with the correct direction. Between 50 and 60% of children wrote <t>, <d>, <p> with the correct direction. The letter <f> was written with the correct direction by only 30% of the children.

## 3.6. Quality

The effect of Letter ( $F(11,53)=12,13, p<.001$  with a large effect size  $\eta^2=.22$ ) and of Condition ( $F(11,63)=62,95, p<.001$  with a large effect size  $\eta^2=.51$ ) were significant. When visual feedback was reduced, the quality decreased ( $M=2.22, SD=0.1$ ) in comparison with the normal writing condition ( $M=2.94, SD=0.07$ ). The effect of interaction was significant ( $F(11,53)=2,74, p=.008$  with a moderate effect size  $\eta^2=.06$ ). Bonferroni post hoc analyses revealed that the difference between the two conditions was significant for all letters ( $p<.05$ ). However, the difference between the two conditions was more or less large depending on the letter (for example <t>, <n> and <i> deteriorated markedly with respectively a mean difference of 1.36, 0.99 and 0.83). Whatever the condition, the letter <f> was drawn with a significantly poorer quality than all the other letters. With reduced visual feedback, <f> was not recognizable in 43% of the productions. The letters <l>, <r>, <p> and <n> obtained significantly higher scores than <a>, <i>, and <t> (Bonferroni post-hoc analyses,  $p<.05$ ).

Table 3 displays the mean marks for quality for each letter.



## 4. Discussion

The objective of this study was to analyze the static and kinematic characteristics of cursive letters produced by young children, and to assess the effect of a modification in visual feedback. The non-inking pen allows children to see their hand and arm, and the spatial position of the pen on the sheet of paper, but they cannot see the written outcome. It prevents them from focusing on the writing trace and on the comparison with the visual model during the production of the letter. Because of the limited working memory capacities, we assume that shape processing could be to the detriment of dynamic aspects.

### 4.1. Characteristics of cursive letter handwriting movement in young children

Even if the children had a blank A4 sheet of paper to write on, the letters they produced remained relatively small in size (trajectory length varied from 2 to 4.7 cm). Before entering primary school, these children demonstrated the ability to control the size of letters even if trajectory length will continue to decrease with development and handwriting acquisition (S  raphin Thibon et al., 2018).

A striking result concerns the high velocity of letter handwriting in young children (for a point of comparison with older children, see S  raphin Thibon et al., 2018). High velocity demonstrates either automation of the gesture (but in this case it is associated with precision and fluency) or low consideration of sensory information (Danna & Velay, 2015) since the use of visual information requires slowing down the movement and making pauses in order to readjust it and increase accuracy. Movements were rapid but highly dysfluent, which seems to indicate that children produced a series of rapid strokes to form the letter. This result is congruent with the idea that at the beginning of handwriting learning, the motor command is at the stroke level rather than at the letter level (S  raphin Thibon et al., 2018).

Young children did not produce numerous penlifts, but when they did make penlifts, their duration was quite long (350 ms). The duration of penlifts is a good indicator of the

cognitive activity during writing (Peverly, 2006). In the context of isolated letters, we assume that long penlifts reveal the lack of stability of the visual and internal motor models and the programming of the movement stroke by stroke. Even if the programming is not at the letter level, children tend to respect the global order of strokes, especially for letters that do not need penlifts or circles.

Handwriting performance was letter dependent, which could be explained by their motor complexity. In previous studies, velocity and number of strokes were used as a measure of motor complexity (Meulenbroek & van Galen, 1990; Séraphin Thibon et al., 2018). With these two criteria <l> appears to be the least complex letter. However, these two criteria do not always combine well. For example, <m>, which contains the highest number of strokes, was not produced with a low velocity. This might be explained by the simplicity of its shape (a repetitive sequence of arcades, with no inversions). The use of only those two criteria to determine motor complexity might not be sufficient and other aspects, such as the shape of the letter or the quality of the handwriting, might be taken into account. For example, the letter <r> was produced with a low velocity but at the same time obtained the highest quality mark. The letter <f>, which was assumed to be of low motor complexity because written rapidly by primary school children (Meulenbroek & van Galen, 1990), obtained the lowest level of quality. What exactly makes a letter difficult to handwrite is not an easy question. A combination of criteria (writing velocity, number of strokes, shape and sequence of strokes) could be used to classify letters. More in-depth studies detailing and contrasting all the criteria that could be considered should make it possible to rank the letters according to their motor complexity. This kind of information might be useful for teachers who need indicators to know which letter to propose when they begin handwriting instruction. Motor complexity could be one of the factors to consider.

In brief, young children were able to write cursive letters before entering primary

school. They already knew some rules for producing letters and were able to control the size and the direction. Their gestures were produced with high velocity but low fluency, which could reflect the difficulty of using visual feedback during the ongoing movement.

### *4.2. Effect of the trace deletion*

The average letter trajectory length was 1.3 times longer when visual feedback was reduced. In skilled handwriting, visual feedback is mainly used to control the size of letters (Marquardt et al., 1999). In grasping movements, a size scaling process, relying on visual input, has been demonstrated in children and adults (Zoia et al., 2006). The initial aperture has been shown to be larger than the target size and to gradually decrease during the movement to match the size of the object (Holmes et al., 2011). We assume that the same process occurs in handwriting. Without updated visual feedback, the large letter size intended in the initial movement plan persists. Feedforward processing is necessary for movement preparation, whereas during the time course of the movement, actual sensory feedback enables adjustment of motor planning (Wolpert et al., 1995). One of the main adjustments may be the size of the motor output. Another explanation for the increase in trajectory length might be that the production of a large movement maximizes proprioceptive feedback. When visual feedback is removed or reduced, participants may tend to compensate by amplifying their movement (Guilbert et al., 2019).

Whatever the letter, velocity and fluency increased when visual feedback was reduced. Young children seem to experience difficulties in using visual sensory feedback during the ongoing movement and tend to produce letters stroke by stroke. The visual template of letters is slowly being built up, as evidenced by children's performance in the visual recognition task (table 1). As internal models for motor control are under development, the constraints on writing with visual feedback are high. We surmise that the visual processing of the writing trace during the movement might increase the cognitive load and deteriorate the movement.

Without the need to process visual information during the ongoing movement, children may place greater emphasis on the gesture. The decrease in the number of penlifts and the improvement in the stroke direction might also illustrate this effect.

An alternative explanation might be that the change in velocity is only the consequence of the increase in trajectory length, as proposed by the isochrony principle. This principle has been shown to apply to drawing since 5 years (Viviani & Schneider, 1991), and to handwriting since first grade (Pagliarini et al., 2017). However, the ratio between trajectory length and mean velocity was not the same in the two writing conditions. When switching from normal to reduced visual feedback, the mean velocity seems to increase more than the length of the trajectories, which suggests that lengthening the trajectories is not the only reason for the increase in velocity.

The reduction in visual feedback deteriorated the quality of letters. Visual feedback has been shown to be more involved in the control of the spatial arrangement of the strokes than the shape (Tucha et al., 2008). Pointing movements in particular depend on the availability of vision (Smyth & Silvers, 1987). It is therefore not surprising that the letters <i> and <t> significantly deteriorated with the absence of a visual trace.

To summarize, the reduction in visual feedback produced strong modifications of the gesture and of the writing outcome. Our results show that without complete visual feedback on letter shape, but with preserved somatosensory feedback and visual feedback on the writing action, kinematic performance seem to be better (higher velocity and fluency, fewer penlifts) but the resulting letter shape is not (lower quality). The results replicate those obtained with older children when visual feedback was removed (Chartrel & Vinter, 2006; Guilbert et al., 2019). While we can describe the results and make assumptions about what they mean, it is difficult to conclude whether this feedback manipulation has positive or negative effects on handwriting. The results could be interpreted either by an improvement in

handwriting (decrease in the number of penlifts, increase in velocity and fluency), or by a deterioration (increase in letter size that impacts velocity, and decrease in quality). In future research it would be interesting to impose size constraints under both writing conditions (writing between two lines for instance) in order to control the effects due to the isochrony principle.

### *4.3. Study limitations*

The children had only one attempt to write the letter and therefore had no possibility of improving their gesture. The deterioration in the quality of the letter can thus be explained by the participants' lack of knowledge of the outcome (Schmidt & Lee, 2005). This handwriting task might be more successful if the child had the opportunity to practice by being informed of the result produced between each trial.

The model of the letter to be copied remained visible during the production. As we did not record eye movements we have no information about how children used the model in the two writing conditions. A compensation mechanism between the absence of feedback on the trace and the presence of the model might have occurred. However, a greater use of the model would have led to an increase in penlifts and a decrease in fluency that we did not observe. As shown by Maldarelli et al. (2015), kindergarten children who copied single letters made more fixations on the model before writing than during writing and rarely looked back at the model.

We did not assess children's motor performance which might affect the ability to copy letters, especially in the reduced visual feedback condition. However, the effect of this inter-subjects variability is reduced because the condition is a within-participants factor.

### *4.4. Educational implications*

The question of feedback has long been considered crucial in instruction (Kluger & DeNisi, 1996). What feedback should be given? At what moment in the process? In what form? This question is especially relevant with very young children who experience difficulty

in integrating different sources of information and who struggle with working memory and attentional constraints (Gori et al., 2008; Maxwell et al., 2003). In handwriting, children could receive extrinsic (from a teacher or a digital device) and/or intrinsic sensory feedback. The interest of increasing visual or auditive feedback during handwriting has already been shown (Bonneton-Botté et al., 2020; Chang & Yu, 2014; Danna et al. 2015). However extrinsic feedback provided during the ongoing movement could also have adverse effects by increasing the processing load (Patchan & Puranik, 2016). One may wonder on the other hand about the value of reducing feedback at certain times.

Different methods could be used to begin handwriting instruction, some of which involve modifying sensory feedback. For example varying the media and tools (writing in sand, flour, in the air, on an erasable screen...) offers children different opportunities to practice handwriting. These ways of teaching are experimented by numerous French kindergarten teachers (Bonneton-Botté et al, 2019). The increasing availability of computers and tablets at school, which offers new opportunities to teach handwriting, also makes it possible to easily modify the sensory feedback (Bonneton-Botté et al., 2020). As these kinds of practice already exist in kindergarten, it is important to draw the attention of practitioners to the fact that these variations in the learning environment have an impact on the learning of the handwriting gesture.

While the legibility of handwriting has been shown to improve with training, it is much more difficult to achieve an improvement in handwriting velocity (Hoy et al., 2011). This aspect of velocity, which is very important in handwriting learning, has however seldom received much attention from teachers (Bonneton-Botté et al., 2019). Modifying availability of visual feedback might help children who struggle with this important acquisition in handwriting. As it is important to develop both the process and the product, exercises that consist in practicing letter handwriting with reduced visual feedback could be combined with

specific visual letter analysis exercises to help students acquire both shape and layout aspects. They could also be combined with exercises that increase somatosensory feedback (Bara & Bonneton-Botté, 2017; Patchan & Puranik, 2016). The variability in motor exercises might be necessary to learn to handwrite and has been interpreted as positive for motor learning in previous studies (Schmidt and Lee, 2005). Even if our study provides food for thought on the question of feedback in handwriting, this question needs to be further investigated through training studies. Only this kind of study would make it possible to make strong recommendations to education professionals.

### 5. Conclusion

At the beginning of letter handwriting learning, children tend to produce letters stroke by stroke, with high velocity but low fluency. Processing visual sensory feedback is cognitively costly for young children. If information on the shape and on the movement are processed simultaneously it can be assumed that a potential conflict during execution between the static and dynamic aspects could occur. When children focus their attention on the trace while they are handwriting, they become aware of the result of the movement segment by segment rather than at the end of the letter. Providing access to the visual trace only at the end of the movement execution (instead of during the movement) may therefore eliminate repeated visual processing of the ongoing trace, which slow down handwriting velocity. Removing visual feedback should promote the use of resources and cognitive efforts toward the kinematic characteristics of the writing gesture. For future research, it would be interesting to specify the optimal time of access to visual feedback during or after execution of the movement, and to analyze the differentiated effects of sensory feedback (integration during movement execution) and knowledge of the result (visual analysis of the static shape as a result of the movement).

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## FEEDBACK IN HANDWRITING ACQUISITION

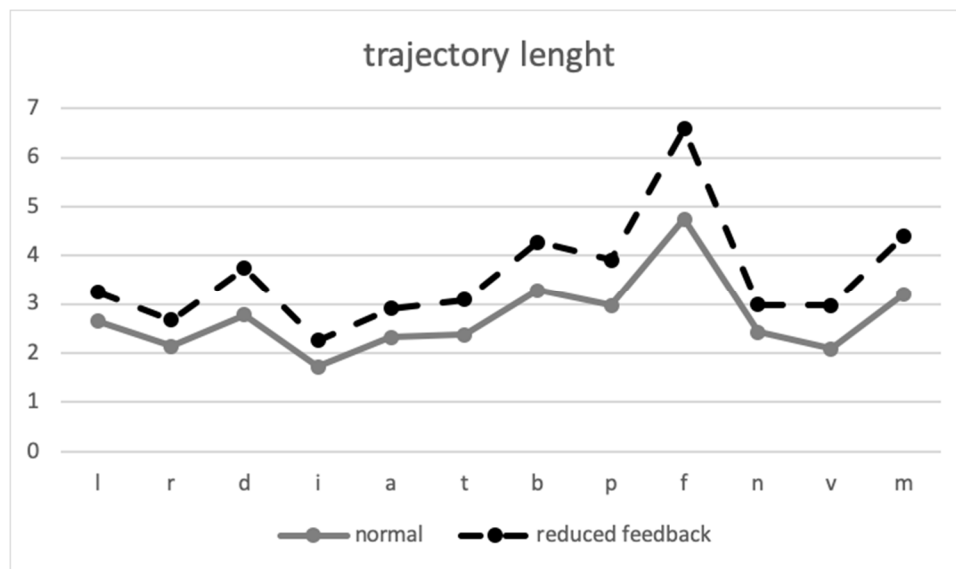
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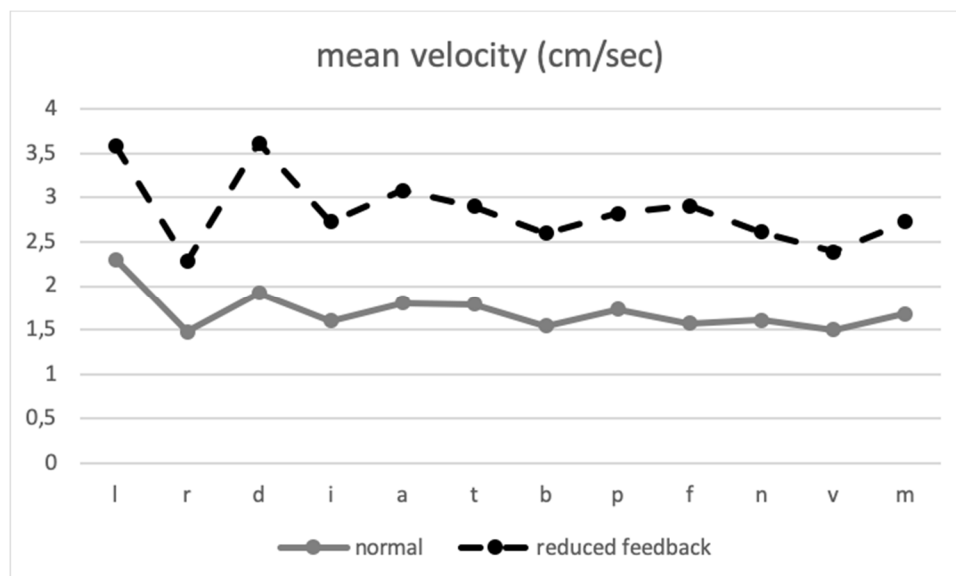
**Figure 1**

*Mean trajectory length for each letter in the two handwriting conditions*



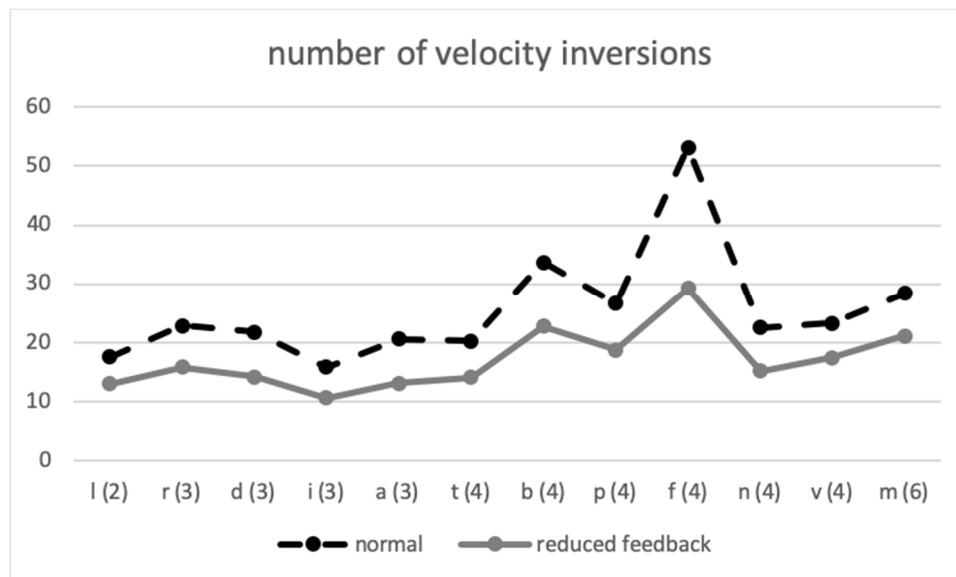
**Figure 2**

*Mean velocity for each letter in the two handwriting conditions*



**Figure 3**

*Mean number of velocity peaks for each letter in the two handwriting conditions*



*Note. The numbers in brackets represent the number of expected strokes in each letter*

**Table 1**

*Percentage of children that correctly recognized the letter*

	a	i	r	l	t	p	b	d	n	f	m	v
Letter recognition	100	98	71.8	70	84.4	60.9	37.5	64	92.2	70.3	90.6	64



**Table 2**

*Mean number and duration of penlifts (M) and standard deviation (SD) for each letter in the two handwriting conditions*

	number of penlifts				duration of penlifts (ms)			
	normal		reduced feedback		normal		reduced feedback	
	M	SD	M	SD	M	SD	M	SD
a	0.69	0.53	0.63	0.49	394.93	235.67	330.52	167.53
i	1.17	0.38	1.08	0.27	360.3	187.47	341.3	242.75
r	0.03	0.17	0	0	515	346.48	0	0
l	0.05	0.21	0	0	426.66	315.6	0	0
t	1.27	0.7	1.09	0.49	244.77	92.46	283.6	165.9
p	0.75	0.62	0.75	0.62	442.62	288.99	411.43	253.86
b	0	0	0.05	0.21	0	0	196.67	141.54
d	0.88	0.7	0.7	0.61	479.15	311.59	377.25	200.77
n	0.11	0.31	0.09	0.29	518.57	447.86	271.67	121.06
f	0.22	0.65	0.13	0.45	390	356.77	364.67	155.83
m	0.27	0.72	0.17	0.58	288.75	145.55	495	242.14
v	0	0	0	0	0	0	0	0

Table 3

*Mean quality mark (M) and standard deviation (SD) for each letter in the two handwriting conditions*

	normal		reduced feedback	
	M	SD	M	SD
a	2.70	1.16	2.02	1.3
i	2.75	0.91	1.92	1.16
r	3.46	1.12	2.86	1.29
l	3.27	1	2.63	1.25
t	3.03	0.86	1.67	1.08
p	3.29	0.94	2.49	1.04
b	2.81	1.27	2.46	1.33
d	2.87	1.07	2.05	1.21
n	3.33	0.8	2.34	1.16
f	1.89	1.44	1.35	1.56
m	2.86	0.91	2.52	1.07
v	2.84	0.79	2.37	1.18