



HAL
open science

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

Florence Bara, Nathalie Bonneton-Botté

► **To cite this version:**

Florence Bara, Nathalie Bonneton-Botté. Handwriting isolated cursive letters in young children: Effect of the visual trace deletion. *Learning and Instruction*, 2021, 74, 10.1016/j.learninstruc.2020.101439 . hal-03404488

HAL Id: hal-03404488

<https://hal.science/hal-03404488v1>

Submitted on 3 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

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

Bara Florence (CLLE-LTC, Université Jean-Jaurès, INSPE, Toulouse)

Bonneton-Botté, Nathalie (LP3C, Université de Bretagne Occidentale, INSPE)

Corresponding author:

Florence Bara

CLLE-LTC, Maison de la recherche

Université de Toulouse Jean-Jaurès

5 allée Antonio-Machado

3110 Toulouse

France

florence.bara@univ-tlse2.fr

Acknowledgment

We would like to sincerely thank the kindergarten children from Jules Ferry, Queliverzan and Kerafloch schools for their participation to the study, and their teachers, who were always willing to test new methods of teaching and to welcome researchers.

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

20 **1. Introduction**

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

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

37 *1.1. Handwriting control and role of feedback*

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

FEEDBACK IN HANDWRITING ACQUISITION

45 informs about the spatial (trajectory and trajectory length), kinematic (velocity, fluency) and
46 dynamic (pressure) characteristics of handwriting movements. Vision is used to monitor the
47 spatial features of handwriting and the size of letters (Marquardt et al., 1999; Tucha et al.,
48 2008). **Visual checking allows precise location of the pen on the writing surface which is**
49 **necessary to produce joins between letters in cursive handwriting and to control the spacing**
50 **between words and between letters in manuscript handwriting.** The lack of vision particularly
51 impairs the production of letters that require pointing movements (Smyth & Silvers, 1987)
52 since these movements (which can be considered as target reaching movements) require an
53 estimation of the position of the hand during the movement, in order to adapt the previously
54 initiated movement towards the final position of the target. This estimation relies heavily on
55 visual information (Saunders & Knill, 2005).

56 The two sources of sensory information are complementary (Hepp-Reymond et al.,
57 2009). In the absence of vision, the system can simulate the movement dynamic by using a
58 forward model and can rely on proprioceptive information to estimate the current location of
59 the hand (Wolpert et al., 1995). Studies that modified the availability of visual feedback
60 showed that children tend to increase trajectory length, pressure and velocity when they do
61 not have complete visual information (Chartrel & Vinter, 2006). Modifying the temporal
62 constraint when writing (increasing the speed) had the same kind of effect by decreasing
63 visual control (Chartrel & Vinter, 2008). The increase in size, which maximizes kinesthetic
64 feedback (Clark & Horch, 1986), has been observed in children, adults and Parkinson's
65 disease (Chartrel & Vinter, 2006; Potgieser et al., 2015; van Doorn & Keuss, 1992). Pressure,
66 which reflects an increase in muscle contraction on the pen, may increase the amount of
67 somatosensory information (Levine et al., 1987). Guilbert et al. (2019) showed an interaction
68 between visual and proprioceptive feedback when writing on a tablet screen. Second and fifth
69 graders and adults wrote letters in four conditions: with or without visual feedback (hand and

FEEDBACK IN HANDWRITING ACQUISITION

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

75 *1.2. Sensory-motor integration and development of motor control*

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

86 When beginning to learn how to write letters, children follow the instructions of the
87 teacher and try to reproduce a model of the letter with respect to its visual shape, the
88 sequentiality of strokes, and the trajectory. Children progressively integrate sensory-motor
89 information that links the sensory input, the motor input and the result (Wolpert et al., 1995).
90 Knowledge of the result produced by the movement is used to modify the next movement
91 attempt (Schmidt & Lee, 2005). The integration of sensory-motor information helps to slowly
92 build the motor program, that goes from strokes to whole letters (S  raphin Thibon et al.,
93 2018). Through comparison with the model from external feedback provided by the teacher or
94 through the child's self-assessment of the deviation of their production from the norm, the best

FEEDBACK IN HANDWRITING ACQUISITION

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

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

106 *1.3. Letter complexity and learning*

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

119 2019). These pointing movements, which strongly characterize manuscript (Graham et al.
120 1998) are also found in cursive writing (letters <i> and <t> for instance).

121 Meulenbroek and van Galen (1986) showed that the most difficult cursive form for
122 primary school children was the wave, which needs a continuous changing movement of wrist
123 and finger. Using a measure of handwriting velocity, Meulenbroek and van Galen (1990)
124 ranked cursive letters according to their level of complexity. The most complex letters were
125 <r> and <z>, which are the only ones to contain horizontally oriented wave form segments.
126 Letters with extenders (e.g. <d>) were more easily written than corpus sized letters (e.g. <a>)
127 probably because a long trajectory induces a faster movement. Writing movements to produce
128 curved lines are less fluent than writing movements for straight lines (S  raphin Thibon et al.,
129 2019). Letter complexity might also be the consequence of the number of strokes. As young
130 children produce letters as a succession of strokes, the cognitive load increases as a function
131 of the number of strokes in the letter (S  raphin Thibon et al., 2018).

132 *1.4. The present study*

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

FEEDBACK IN HANDWRITING ACQUISITION

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

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

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

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

176 **2. Method**

177 *2.1. Participants*

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

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

FEEDBACK IN HANDWRITING ACQUISITION

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

197 *2.2. Material*

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

201 Twelve letters of the alphabet (<a>, <i>, <r>, , <f>, <m>, <d>, <n>, <t>, <v>, <l>,
202 <p>) were chosen. Except for <f> and <v> (which had never been practiced in class), these
203 letters are frequently proposed by preschool teachers at the beginning of instruction. The
204 selected letters vary in terms of the projection axis, aperture, trajectory length, and direction.
205 They have different levels of motor complexity: wave (<m>, <v>, <n>), loops (<l>,),
206 extenders (<d>, <t>, <p>), inversions (<v>), rotation (<a>, <d>) (Meulenbroek & van Galen,
207 1990), pointing movements (<t>, <i>) (S raphin Thibon et al., 2019) and different numbers of
208 strokes (<l>, <m>) (S raphin Thibon et al., 2018). The model of the letter was in cursive
209 handwriting (which is the usual type of script taught in French schools).

210 *2.3. Procedure*

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

215 Each child participated in two handwriting conditions:

216 - with visual feedback: the child used an inking pen to write the letters;

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

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

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

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

234 *2.4. Assessment of letter handwriting product and process*

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

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

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

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

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

263 *2.5. Data Analysis*

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

267 **3. Results**

268 *3.1. Trajectory length*

FEEDBACK IN HANDWRITING ACQUISITION

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

277 3.2. Mean velocity

278 The analysis revealed a significant effect of Letter ($F(11,53)=7.49$, $p<.001$, with a large
279 effect size $\eta^2=.22$) and of Condition ($F(11,63)=118.76$, $p<.001$ with a large effect size
280 $\eta^2=.65$). The interaction was significant ($F(11,53)=15.69$, $p<.001$, with a large effect size
281 $\eta^2=.34$). When visual feedback was reduced, mean velocity improved ($M=2.86$; $SD=0.14$) in
282 comparison with the normal writing condition ($M=1.72$; $SD=0.08$). Bonferroni post hoc
283 analyses revealed that the difference between the two conditions was significant for all letters
284 ($p<.05$). However, this difference was more or less large depending on the letter: for example,
285 <l> and <a> exhibited a marked difference between the conditions (see Fig. 2). Whatever the
286 condition, the letters <l> and <d> differed significantly from all the other letters and were
287 drawn with the highest velocity. Letter <r> differed from the others and was drawn with a
288 significantly lower velocity than <a>, <i>, <l>, <t>, <p> and <d>. The letter <v> was drawn
289 with a lower velocity than <a>, <l>, <t>, and <d> (Bonferroni post-hoc analyses, $p<.01$). The
290 other letters did not differ significantly from each other (Bonferroni post-hoc analyses,
291 $p<.01$).

292 3.3. Fluency (number of velocity inversions/number of expected strokes)

FEEDBACK IN HANDWRITING ACQUISITION

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

304 *3.4. Number of penlifts and mean duration (ms)*

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

313 Concerning the duration of penlifts, a significant effect of Letter ($F(11,53)= 51.04,$
314 $p<.001$, with a large effect size $\eta^2=.91$), and of Condition ($F(11,63)=11.48, p<.001$, with a
315 large effect size $\eta^2=.15$) was found. The effect of interaction was not significant. When
316 penlifts occurred, their duration was longer in the normal writing condition ($M=406.07;$
317 $SD=272.8$) than when visual feedback was reduced ($M=307.21; SD=187.9$).

FEEDBACK IN HANDWRITING ACQUISITION

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

319 3.5. Stroke order

320 A paired-sample t-test was performed on the number of letters written with the
321 conventional stroke order. It revealed a significant effect of the writing condition ($t(63)=-$
322 $3.54, p<.001$). The mean number of letters written with the conventional stroke order was
323 significantly higher with reduced visual feedback ($M=9.69, SD=1.85$) than in the normal
324 writing condition ($M=9.09, SD=2.24$). In the normal writing condition around 90% of the
325 children were able to write <r>, <l>, <n>, <v>, and <m> with the conventional stroke
326 order. Around 70% of the children wrote <a> and <i> with the correct direction. Between 50
327 and 60% of children wrote <t>, <d>, <p> with the correct direction. The letter <f> was
328 written with the correct direction by only 30% of the children.

329 3.6. Quality

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

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

343 **4. Discussion**

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

351 *4.1. Characteristics of cursive letter handwriting movement in young children*

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

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

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

FEEDBACK IN HANDWRITING ACQUISITION

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

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

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

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

396 *4.2. Effect of the trace deletion*

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

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

FEEDBACK IN HANDWRITING ACQUISITION

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

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

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

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

FEEDBACK IN HANDWRITING ACQUISITION

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

448 *4.3. Study limitations*

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

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

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

464 *4.4. Educational implications*

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

FEEDBACK IN HANDWRITING ACQUISITION

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

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

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

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

501

502 **5. Conclusion**

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

518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542

References

Accardo, A. P., Genna, M., & Borean, M. (2013). Reprint of development, maturation and learning influence on handwriting kinematics. *Human Movement Science, 32*, 999–1009.

Bara, F. & Morin, M-F. (2013). Does the handwriting style learnt in first grade determine the style used in fourth and fifth grade and influence handwriting speed and quality ? A comparison between French and Quebec children. *Psychology in the Schools, 50(6)*, 601-617.

Bodegard, A., Geyer, S., Herath, P., Grefkes, C., Zilles, K., & Roland, P.E. (2003). Somatosensory areas engaged during discrimination of steady pressure, spring strength, and kinesthesia. *Human Brain Mapping, 20(2)*, 103-115.

Bara, F., & Bonneton-Botté, N. (2017). Learning letters with the whole body: Visuomotor vs visual teaching in kindergarten. *Perceptual and Motor Skills, 125(1)*, 190–207

Bonneton-Botté, N., Beucher, C., Bara, F., Dare, M., Le Corf, L., Muller, J., & Quemeneur, M. (2019). Teaching cursive handwriting in France: a contribution to the acceptability study of using digital tablets in French classrooms. *Journal of Early Childhood Literacy*. doi:10.1177/1468798419838587

Bonneton-Botté, N., Fleury, S., Girard, N., Le Magadou, M., Cherbonnier, A., Renault, M., Anquetil, E., & Jamet, E. (2020). Can tablet apps support the learning of handwriting? An investigation of learning outcomes in kindergarten classroom. *Computers & Education, 151*, 103831. doi:10.1016/j.compedu.2020.103831

Chang, S. H., & Yu, N. Y. (2014). The effect of computer-assisted therapeutic practice for children with handwriting deficit: A comparison with the effect of the traditional sensorimotor approach. *Research in Developmental Disabilities, 35*, 1648–1657.

FEEDBACK IN HANDWRITING ACQUISITION

- 543 Chartrel, E., & Vinter, A. (2006). Rôle des informations visuelles dans la production de lettres
544 cursives chez l'enfant et l'adulte {Role of visual information in the production of
545 cursive letters in children and adults}. *L'Année Psychologique*, 106, 45–66.
- 546 Chartrel, E., & Vinter, A. (2008). The impact of spatio-temporal constraints on cursive letter
547 handwriting in children. *Learning and Instruction*, 18, 537–547.
- 548 Clark, F. J., & Horch, K. W. (1986). Kinesthesia. In Boff, K.B., Kaufman, L., & Thomas, J.B
549 (eds). *Handbook of perception and human performance, vol1: Sensory processes and*
550 *performance*. New-York: Wiley.
- 551 Danna, J., Fontaine, M., Paz-Villagran, V., Gondre, C., Thoret, E., & et al. (2015). The effect
552 of real-time auditory feedback on learning new characters. *Human Movement Science*,
553 43, 216–228
- 554 Danna, J., & Velay, J. L. (2015). Basic and supplementary sensory feedback in handwriting.
555 *Frontiers in Psychology*. 6:169. doi 10.3389/fpsyg.2015.00169
- 556 Danna, J., Paz-Villagran, V., & Velay, J-L. (2013). Signal-to-Noise velocity peaks difference:
557 A new method for evaluating the handwriting movement fluency in children with
558 dysgraphia. *Research in Developmental Disabilities*, 34, 4375-4384.
- 559 Fears, N., & Lockman, J. (2018). How beginning handwriting is influenced by letter
560 knowledge: visual-motor coordination during children's form copying. *Journal of*
561 *Experimental Child Psychology*, 171, 55–70.
- 562 Feder, K., Majnemer, A., Bourbonnais, D., Blayney, M., & Morin, I. (2007). Handwriting
563 performance on the ETCH-M of students in a grade one regular education program.
564 *Physical & Occupational Therapy in Pediatrics*, 27(2), 43–62.
- 565 Goodnow, J. J., & Levine, R. A. (1973). "The grammar of action": Sequence and syntax in
566 children's copying. *Cognitive Psychology*, 4, 82–98.

FEEDBACK IN HANDWRITING ACQUISITION

- 567 Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate
568 visual and haptic form information. *Current Biology*, 18(9), 694–698.
- 569 Graham, S., Berninger, V. W., & Weintraub, N. (1998). The relationships between
570 handwriting style and speed and legibility. *Journal of Educational Research*, 5, 290–
571 296.
- 572 Guilbert, J., Alamargot, D., & Morin, M. F. (2019). Handwriting on a tablet screen: Role of
573 visual and proprioceptive feedback in the control of movement by children and adults.
574 *Human Movement Science*, 65, 30–41.
- 575 Guinet, E., & Kandel, S. (2010). Ductus: A software package for the study of handwriting
576 production. *Behavior Research Methods*, 42(1), 326-332.
- 577 Halsband, U., & Lange, R. K. (2006). Motor learning in man: a review of functional and
578 clinical studies. *Journal of Physiology*, 99(4–6), 414–424.
- 579 Hay, L. (1979). Spatial-temporal analysis of movements in children: motor programs versus
580 feedback in the motor development of reaching. *Journal of Motor Behavior*, 11(3),
581 189-200.
- 582 Hepp-Reymond, M. C., Chakarov, V., Schulte-Monting, J., Huethe, F., & Kristeva, R. (2009).
583 Role of proprioception and vision in handwriting. *Brain Research Bulletin*, 79(6),
584 365–370.
- 585 Holmes, S.A., Mulla, A., Binsted, G., & Heath, M. (2011). Visually and memory-guided
586 grasping: aperture shaping exhibits a time-dependent scaling to Weber’s law. *Vision*
587 *Research*, 51 (17), 1941–1948.
- 588 Hoy, M. M., Egan, M. Y., & Feder, K. (2011). A systematic review of interventions to
589 improve handwriting. *Canadian Journal of Occupational Therapy*, 78(1), 13–25.
- 590 Kao, H.S.R, Hoosain, R., & van Galen, G.P. (1986). *Graphonomics: Contemporary Research*
591 *in Handwriting*. Amsterdam: North Holland.

FEEDBACK IN HANDWRITING ACQUISITION

- 592 Kluger, A.N., & DeNisi, A. (1996). The effects of feedback interventions on performance: a
593 historical review, a meta-analysis, and a preliminary feedback intervention theory,
594 *Psychological Bulletin*, 119, 254–284.
- 595 Lacquaniti F, Terzuolo, C., & Viviani, P. (1983). The law relating the kinematic and figural
596 aspects of drawing movements. *Acta Psychologica*, 54(1-3), 115-130.
- 597 Levine, M. D., Gordon, B. N., & Reed, M. S. (1987). *Developmental variation and learning*
598 *disorders*. Educators Publishing Service.
- 599 Maldarelli, J.E., Kahrs, B.A., Hunt, S.C., & Lockman, J.J. (2015). Development of early
600 handwriting: Visual-motor control during letter copying. *Developmental Psychology*,
601 51(7), 879-888.
- 602 Marquardt, C., Gentz, W., & Mai, N. (1999). Visual control of automated handwriting
603 movements. *Experimental Brain Research* 128 (1), 224–228.
- 604 Maxwell, J. P., Masters, R. S. W., & Eves, F. F. (2003). The role of working memory in
605 motor learning and performance. *Consciousness and Cognition*, 12(3), 376–402.
- 606 Meulenbroek, R. G., & van Galen, G. (1986). Movement analysis of repetitive writing
607 behavior of first, second and third grade primary school children. In H. S. R. Kao, G.
608 van Galen, & R. Hoosain (Eds.), *Graphonomics: Contemporary research in*
609 *handwriting* (pp. 71–92). Amsterdam: North-Holland.
- 610 Meulenbroek, R.G., & van Galen, G. (1988). The acquisition of skilled handwriting:
611 discontinuous trends in kinematic variables. *Advances in Psychology*, 55, 273-281.
- 612 Meulenbroek, R.G., & van Galen, G. (1990). Perceptual-motor complexity of printed and
613 cursive letters. *The Journal of Experimental Education*, 58(2), 95-110.
- 614 Meulenbroek, R. G., Vinter, A., & Mounoud, P. (1993). Development of the start-rotation
615 principle in circle production. *British Journal of Developmental Psychology*, 11, 307–
616 320.

FEEDBACK IN HANDWRITING ACQUISITION

- 617 Pagliarini, E., Scocchia, L., Vernice, M., Zoppello, M., Balottin, U., Bouamama, S., Guasti,
618 M.T., & Stucchi, N. (2017). Children's first handwriting productions show a rhythmic
619 structure. *Scientific Reports*, 7: 5516 | doi:10.1038/s41598-017-05105-6.
- 620 Patchan, M. M., & Puranik, C. (2016). Using tablet computers to teach preschool children to
621 write letters: Exploring the impact of extrinsic and intrinsic feedback. *Computers &*
622 *Education*, 102, 128–137.
- 623 Paz-Villagran, V., Danna, J., & Velay, J. L. (2014). Lifts and stops in proficient and
624 dysgraphic handwriting. *Human Movement Science*, 33, 381–394.
- 625 Peverly, S. T. (2006). The importance of handwriting speed in adult writing. *Developmental*
626 *Neuropsychology*, 29, 197–216. doi: 10.1207/s15326942dn2901_10
- 627 Potgieser, A.R., Roosma, E., Beudel, M., & de Jong, B.M. (2015). The effect of visual
628 feedback on writing size in Parkinson's disease. *Parkinson Disease*. 2015:857041.doi:
629 10.1155/2015/857041
- 630 Rosenblum, S., Weiss, P. L., & Parush, S. (2003). Product and process evaluation of
631 handwriting difficulties. *Educational Psychology Review*, 15, 41–81.
- 632 Saunders, J. A., & Knill, D. C. (2005). Humans use continuous visual feedback from the hand
633 to control both the direction and distance of pointing movements. *Experimental Brain*
634 *Research*, 162(4), 458-473.
- 635 Schmidt, R. A., & Lee, T. D. (2005). *Motor control and learning. A behavioral emphasis* (5th
636 ed.). Champaign, IL: Human Kinetics.
- 637 Séraphin Thibon, L., Barbier, G., Vilain, C., Sawallis, T., Gerber, S., & Kandel, S. (2019).
638 Investigating how children produce rotation and pointing movements when they learn
639 to write letters. *Human Movement Science*, 65, 15-29.
- 640 Séraphin Thibon, L., Gerber, S., & Kandel, S. (2018). The elaboration of motor programs for
641 the automation of letter production. *Acta Psychologica*, 182, 200–211.

FEEDBACK IN HANDWRITING ACQUISITION

- 642 Smyth, M. M., & Silvers, G. (1987). Functions of vision in the control of handwriting. *Acta*
643 *Psychologica*, 65(1), 47-64.
- 644 Summers, J. J., & Anson, J. G. (2009). Current status of the motor program: revisited. *Human*
645 *Movement Science*, 28, 566–577.
- 646 Tucha, O., Tucha, L., & Lange, K. W. (2008). Graphonomics automaticity and handwriting
647 assesment. *Literacy*, 42(3), 145–155.
- 648 van Doorn, R.R.A., & Keuss, P.J.G. (1992). The role of vision in the temporal and spatial
649 control of handwriting. *Acta Psychologica*, 81 (3), 269–286.
- 650 Viviani, P. & Schneider, R. A. (1991). Developmental Study of the Relationship Between
651 Geometry and Kinematics in Drawing Movements. *Journal of Experimental*
652 *Psychology: Human Perception Performance*, 17, 198-218.
- 653 Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor
654 learning. *Nature Review Neuroscience*, 12, 739–751.
- 655 Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor
656 integration. *Science*, 269(5232), 1880–1882.
- 657 Zoia, S., Pezzetta, E., Blason, L., Scabar, A., Carrozzini, M., & Bulgheroni, M. (2006). A
658 comparison of the reach-to-grasp movement between children and adults: A kinematic
659 study. *Developmental Neuropsychology*, 30(2), 719-738.
- 660
- 661

Figure 1

Mean trajectory length for each letter in the two handwriting conditions

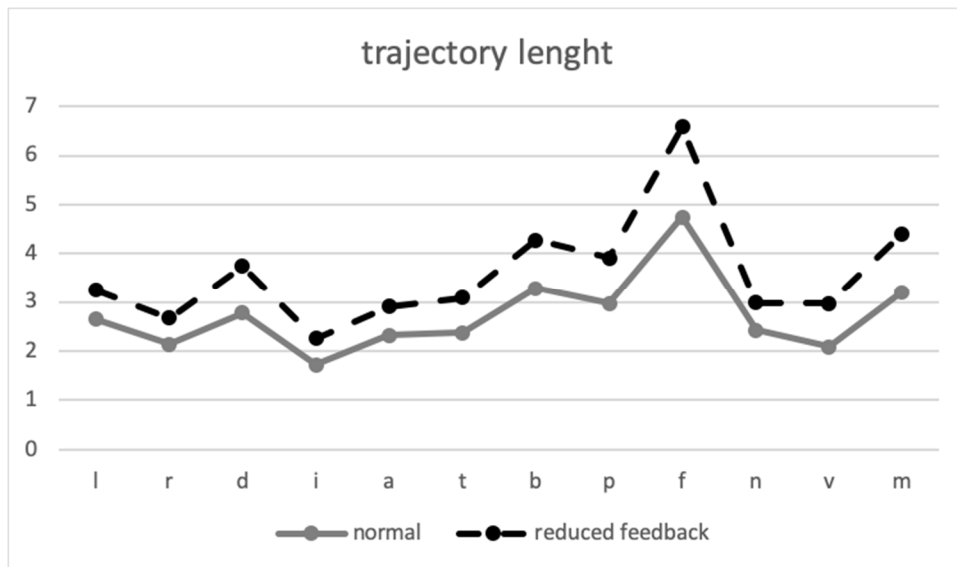


Figure 2

Mean velocity for each letter in the two handwriting conditions

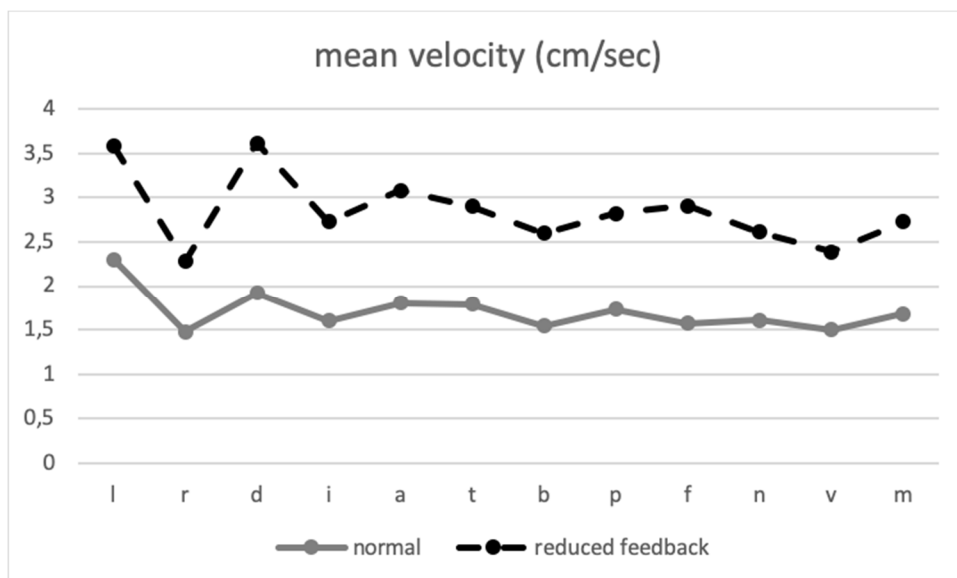
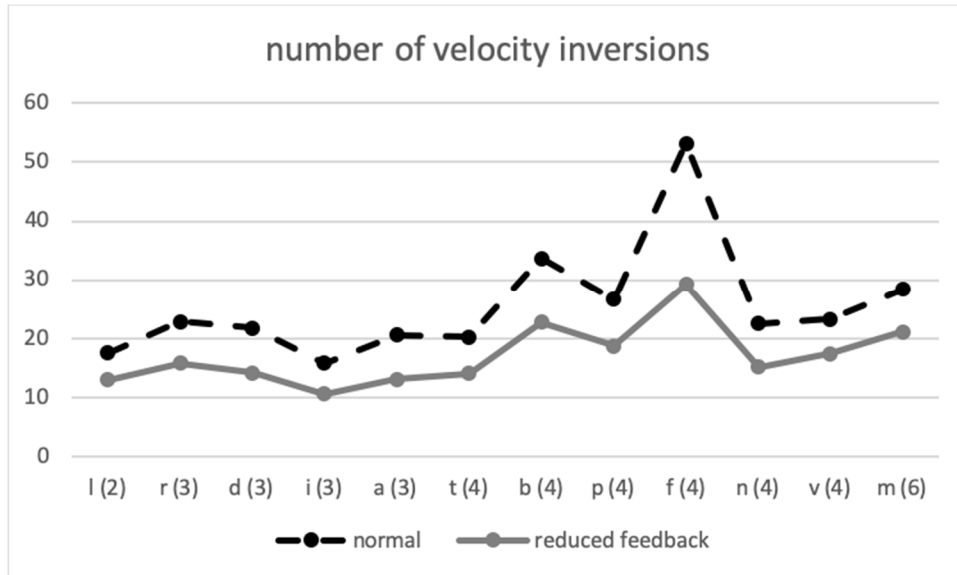


Figure 3

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 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