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► **To cite this version:**

Jessica Guilbert, Denis Alamargot, Marie-France Morin. Handwriting on a tablet screen: Role of visual and proprioceptive feedback in the control of movement by children and adults. *Human Movement Science*, 2019, 65, pp.30-41. 10.1016/j.humov.2018.09.001 . hal-02779093

HAL Id: hal-02779093

<https://hal.science/hal-02779093>

Submitted on 25 Oct 2021

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Handwriting on a tablet screen: Role of visual and proprioceptive feedback in the control of movement by children and adults

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26 In addition, our results on the impact of tablet surface on graphomotor execution will serve as
27 useful pointers for improving the design of this tool for children, such as increasing the degree
28 of friction of the screen surface.

29 *Keywords:* Handwriting, vision, proprioception, graphomotor execution, digital tablet, writing
30 development

31

1. Introduction

1.1. Writing and Digital Tools

With reading and mathematical skills, handwriting is a core skill that children must acquire during their school career. However, the development of writing abilities is long, complex and involves the coordination of cognitive, motor, perceptual, attentional and linguistic skills (Jolly, Palluel-Germain, & Gentaz, 2013). Given the increasing presence of digital tools in the classroom, learning to write involves not only the practice of handwriting with pen on paper, but also the use of a variety of tools (e.g., real or virtual keyboard, pen or finger on a tablet surface) (for a review, see Mangen & Balsvik, 2016; Wollscheid, Sjaastad, & Tømte, 2016). Given their interactive nature, these new technologies can be used to deliver more individualized instructions and immediate feedback (e.g., Girard, Simonnet, & Anquetil, 2017; Patchan & Puranik, 2016). Thus, these tools make it possible to give children exercises that are better adapted to their level of learning. For instance, training on a tactile interface that includes writing exercises with videos showing how to correctly form each letter has been found to improve writing fluency in 5-year-olds (Jolly et al., 2013). Recently, Patchan and Puranik (2016) showed that preschool children who practise writing with their finger on a tablet screen are able to write more letters correctly than children who practise with a stylus on the screen.

Although these results look promising, more studies need to be conducted to determine the cognitive and graphomotor constraints imposed by these new tools. For instance, the low-friction surface of a tablet screen generates a sensation of sliding over a slippery surface that disturbs graphomotor execution in both children and adults (Alamargot & Morin, 2015; Gerth, Dolk et al., 2016; Gerth, Klassert et al., 2016). Consequently, by modifying the usual writing conditions, these new media may make it more difficult for

56 writers to perform their handwriting movements, especially unskilled writers, who control
57 their movements differently from experienced writers.

58 **1.2. Use of Sensory Feedback During Handwriting Development**

59 The acquisition of handwriting skills is characterized by a nonlinear improvement in
60 both handwriting legibility, which considers the writing product, and kinematics (writing
61 process), which provides information on the motor control mechanisms (Meulenbroek & Van
62 Galen, 1988; for a review, see Palmis, Danna, Velay, & Longcamp, 2017). Between 7 and 10
63 years, a transition takes place that has been interpreted as a shift from the online control of
64 movement, based on sensory feedback (retroactive control), to predictive motor control, based
65 mainly on the execution of motor programmes (proactive control) (Meulenbroek & Van
66 Galen, 1988; Zesiger, Deonna, & Mayor, 2000). Before the age of 10 years, writing
67 movement is slow and dysfluent, reflecting the extensive use of visual and kinaesthetic
68 feedback, which disrupts the normally smooth execution of letter segments (Meulenbroek &
69 Van Galen, 1988). Young children tend to exert strong pressure on the pen, denoting
70 considerable muscle tension and general motor involvement during handwriting (Zesiger et
71 al., 2000). They also tend to produce large letters, although letter size gradually decreases to
72 meet school requirements, notably between the first and second grades (Charles, Soppelsa, &
73 Albaret, 2004; Chartrel & Vinter, 2008). These kinematic characteristics reveal that young
74 writers have not yet memorized the correct motor patterns and predominantly rely on the use
75 of visual and kinaesthetic feedback for a twofold purpose: controlling step by step the
76 ongoing movements involved in the production of letter shapes (morphokinetic movements)
77 and those responsible for the spatial layout of the letters in the graphic space (topokinetic
78 movements). At around 9-10 years, the motor programmes dedicated to the production of
79 each letter become memorized in long-term memory (Zesiger et al., 2000). Movement
80 velocity, fluency and legibility increase, while handwriting size, pen pressure, and the number

81 and duration of pauses between two segments decrease (Accardo, Genna, & Borean, 2013;
82 Chartrel & Vinter, 2006; Meulenbroek & Van Galen, 1988; Vinter & Chartrel, 2010). This
83 developmental change in kinematic parameters reflects the improvement in predictive motor
84 control. Letter formation is now programmed before the onset of movement. More
85 specifically, once the motor programmes have been retrieved, information about movement
86 parametrization and muscular adjustments is used to update the motor commands, in order to
87 produce the desired letter shapes. The role of sensory feedback is therefore to confirm that
88 everything goes according to plan (Danna & Velay, 2015; Palmis et al., 2017). Although
89 movement components start to be included in motor programmes at around the age of 9-10
90 years, fluency and speed continue to improve across adolescence (Accardo et al., 2013,
91 Rueckriegel et al., 2008). Furthermore, adolescents gradually learn to strike the best
92 compromises between legibility and speed requirements, depending on the handwriting
93 context (Chartrel & Vinter, 2004).

94 In sum, less experienced writers, who have not yet stored any motor programmes,
95 predominantly use sensory information to guide their handwriting movements. Thus, when
96 Chartrel and Vinter (2006) explored the impact of withdrawing visual feedback during the
97 execution of cursive letters in 8-, 9-, 10-year-olds and adults, they found that the handwriting
98 performances of the children were far more affected than those of the adults. More
99 specifically, in the children, movement length, movement velocity, and pen pressure all
100 increased in the absence of visual information, whereas only pen pressure increased in adults.
101 According to the authors, these results suggest that children (and, to a much lesser extent,
102 adults) compensate for the absence of visual information by maximizing proprioceptive
103 feedback to guide their movements. In addition to the growing independence from visual
104 feedback for controlling movement, the gradual improvement in predictive motor control
105 during childhood may be the consequence of an increasing ability to process and integrate the

106 different sources of afferent information (notably visual and kinaesthetic) (von Hofsten &
107 Rosblad, 1988). However, the weakness of kinaesthetic acuity observed until at least 7 years
108 of age prevents preschool children from accurately integrating proprioceptive feedback for
109 online control of movement (Bairstow & Laszlo, 1981; Laszlo & Bairstow, 1984). At around
110 7 years, children begin to make appropriate use of proprioceptive feedback to correct their
111 ongoing movement. However, this source of information cannot be weighed against visual
112 information (Chicoine, Lassonde, & Proteau, 1992; Laszlo & Bairstow, 1984). As indicated
113 by Chicoine et al. (1992) for aiming movement, before 9 years of age, the different sources of
114 afferent signals are processed independently of each other. It is only at around 8-10 years that
115 signals from multiple modalities start to be integrated in a statistically optimal manner, where
116 each sense is weighted in proportion to its relative reliability in a given condition (Gori, Del
117 Viva, Sandini, & Burr, 2008).

118 The formation of motor programmes means that the control of morphokinetic
119 movement in adults is much less dependent on sensory feedback than it is in children
120 (Chartrel & Vinter, 2006). However, even in adults, motor control cannot be exclusively
121 proactive: sensory information continues to be used for the execution of motor programmes,
122 but in a monitoring function instead of the moment-to-moment regulation of movements
123 exhibited by young writers (Marquardt, Gentz, & Mai 1999; Van Galen, Smyth,
124 Meulenbroek, & Hylkema, 1989). Concerning the role of visual feedback, several studies
125 have shown that deprivation or modification of vision during handwriting leads to writing
126 errors such as additional strokes, especially for letters with repetitive strokes (Smyth &
127 Silvers, 1987; Tamada, 1995) and to increased movement duration (Van Doorn & Keuss,
128 1992; Van Galen et al., 1989), though not systematically (Smyth & Silvers, 1987). As
129 indicated by Smyth and Silvers (1987), visual feedback may be important for maintaining
130 order in the output sequence. A number of studies have reported that the withdrawal of visual

131 feedback during handwriting has no effect on automatic movement execution (Marquardt,
132 Gentz, & Mai, 1996; Tucha, Tucha, & Lange, 2008). For instance, Marquardt et al. (1996)
133 showed that velocity profiles (number of inversions in velocity) remained unchanged when
134 adults had to write combinations of characters with their eyes closed. Conscious attention to
135 visual feedback has, however, been found to disturb handwriting automaticity. According to
136 Tucha et al. (2008), visual feedback is used not to control the writing movement, but to
137 monitor the spatial features of the handwriting (stroke size, form and positioning of letters).
138 By contrast, proprioceptive feedback is essential for controlling the kinematics and dynamics
139 of handwriting movements, as demonstrated by studies with deafferented patients
140 characterized by the loss of cutaneous and proprioceptive sensation (e.g., Hepp-Reymond,
141 Chakarov, Schulte-Mönting, Huethe, & Kristeva, 2009; Teasdale, Forget, Bard, Paillard,
142 Fleury, & Lamarre, 1993). When Hepp-Reymond et al. (2009) asked a deafferented patient to
143 write the word *parallele* with and without visual control, they observed an increase in the
144 number of pen touches and inversions in velocity, and a decrease in mean stroke frequency,
145 revealing a strong impairment in automated behaviour whatever the vision condition. For
146 their part, Teasdale et al. (1993) showed that deafferented patients may compensate for the
147 absence of proprioceptive information by relying more heavily on visual feedback to control
148 the spatial organization of their writing. The role of proprioceptive feedback has also been
149 investigated in healthy individuals by varying the degree of friction with the handwriting
150 surface (Chan & Lee, 2005; Wann & Nimmo-Smith, 1991). The results of these studies
151 revealed that handwriting speed (Chan & Lee, 2005) and pen pressure (Wann & Nimmo-
152 Smith 1991) were modified when adult participants were asked to write on a low-friction
153 surface. As indicated by Alamargot and Morin (2015), experienced writers are sensitive to the
154 kinematics of handwriting movement, and in this situation, use the strategy of increasing
155 frictional force to achieve an input–output dynamic similar to that of a classic writing surface.

156 **1.3. Handwriting on the Screen of a Tablet Computer**

157 Writing on the low-friction surface of a tablet screen produces a sensation of sliding
158 over a slippery surface and thus induces a modification in the proprioceptive feedback needed
159 to control movement. Recently, some studies have investigated whether the modification in
160 proprioceptive information induced by the smooth screen of tablet computer impacts
161 handwriting movements (Alamargot & Morin, 2015; Gerth, Dolk et al., 2016; Gerth, Klassert
162 et al., 2016). This issue has been explored in both children (Alamargot & Morin, 2015; Gerth,
163 Klassert et al., 2016) and adults (Gerth, Dolk et al., 2016; Gerth, Klassert et al., 2016).
164 Alamargot and Morin (2015) compared movement kinematics when second and ninth graders
165 had to write either with a plastic-tipped pen on a tablet screen or with a ballpoint pen on
166 paper. Their results revealed that when participants had to write on the tablet screen, younger
167 writers tended to make longer pauses, revealing a disturbance in segment trajectory
168 calculation, whereas older writers increased both pen pressure and pen speed, reflecting a
169 disturbance in the online regulation of initial motor commands.

170 Gerth, Dolk et al. (2016) extended this result by revealing that, even in experienced
171 writers, graphomotor execution is modified (notably with a higher velocity) when participants
172 are asked to write a sentence or copy a loop pattern or geometric forms on a tablet screen.
173 Concerning sentence writing, there was a significant increase in velocity, writing duration, in
174 air time, and numbers of pen lifts and inversions in velocity. However, the degree of
175 handwriting adaptation depended on the task demands. In a second study, Gerth, Klassert et
176 al. (2016) confirmed that the difference in movement execution between writing on a tablet
177 and writing on paper is partly task-dependent, both in adults and in children.

178 **1.4. Overview**

179 In sum, this series of recent studies found that when the smoothness of a tablet screen
180 modifies proprioceptive feedback, the impact on graphomotor execution varies according to

181 the level of the writer's handwriting skills (Alamargot & Morin, 2015; Gerth, Dolk et al.,
182 2016; Gerth, Klassert et al., 2016). However, as the writing on the screen remained visible in
183 these studies, participants may have compensated for the decrease in proprioceptive feedback
184 by relying more heavily on visual information. The aim of the present study was thus to
185 unravel the respective contributions of visual and proprioceptive feedback during handwriting
186 development and, consequently, the compensatory role of visual information when children
187 and adults have to write on a tablet. Because development is characterized by changes in the
188 use of sensory feedback to control movement, we compared the handwriting performances of
189 three different age groups: 7-year-olds (second graders), 11-year-olds (fifth graders), and
190 adults. We chose these ages because they correspond to periods before, during and after motor
191 programme acquisition. As indicated in the literature (Chartrel & Vinter, 2006, 2008;
192 Meulenbroek & Van Galen, 1988; Vinter & Chartrel, 2010; Zesiger et al., 2000), at around
193 7-8 years, children predominantly rely on the use of sensory feedback to control their
194 handwriting movement step by step (retroactive control). Proactive motor control emerges at
195 around 10 years (Blöte & Hamstra-Bletz, 1991; Chartrel & Vinter, 2006, 2008; Vinter &
196 Chartrel, 2010), with the development of motor programmes. The improvement in proactive
197 motor control across childhood reflects an increasing ability to integrate proprioceptive
198 information with vision (von Hofsten & Rosblad, 1988). Finally, in adults, whose motor
199 programmes are completely automated, sensory feedback is reduced to a monitoring function.

200 As many researchers recognize that handwriting is organized hierarchically (Smyth &
201 Silvers, 1987; Tamada, 1995), we administered two handwriting tasks that varied in the
202 degree of sequencing for the items to be written: a letter-handwriting task involving the
203 production of five isolated letters; and a pseudoword-handwriting task involving the
204 production of three different sequences of letters. A motor plan for handwriting can be viewed
205 as a representation of the serial order of the different subunits (e.g., strokes, letters)

206 composing the item to be produced (e.g., letter, word). Thus, writing a word or a pseudoword
207 needs the order of letters or letter combinations to be programmed, while writing a letter
208 needs the order of the strokes to be programmed. The order of an output sequence is not fully
209 determined in advance, but adjusted on the basis of sensory feedback (Smyth & Silvers, 1987),
210 especially when there is a high degree of sequencing.

211 In order to better understand the respective roles of visual and proprioceptive feedback
212 during handwriting movements, participants wrote on either the smooth or the granular side of
213 the plastic board (manipulation of surface friction) and either with their eyes open or with a
214 shield that prevented them from receiving visual feedback about their hand and what they had
215 written so far (manipulation of vision). We performed a twofold analysis based on letter
216 legibility and handwriting kinematics to assess handwriting performances. We expected the
217 smooth writing surface to make it more difficult for participants to execute their handwriting
218 movements, especially when they were unable to see their hand and their handwriting. More
219 precisely, we expected to observe disturbances in the handwriting kinematics (handwriting
220 process) and, possibly, in the legibility of the letters (handwriting product) with the lower-
221 friction surface, especially when visual information was withdrawn. This prediction was
222 based on previously reported data showing that writers compensate when deprived of either
223 visual or proprioceptive (deafferented individuals) information, suggesting that both systems
224 contribute to handwriting control. We therefore reasoned that participants would maximize
225 their proprioceptive feedback by increasing pen pressure, letter size and, as a consequence
226 (isochrony principle), movement velocity, especially when sensory information
227 (proprioceptive and/or visual) was reduced. In accordance with the developmental trend
228 observed for handwriting control, we also assumed that these adjustments would be more
229 pronounced in children than in adults. Because development is characterized by an overall
230 reduction in the use of feedback to control movement, we expected the withdrawal of visual

231 information and reduction in proprioceptive information induced by the smooth side of the
232 tablet screen to disturb the children's handwriting performances more than the adults'.

233

2. Method

234 2.1. Participants

235 We recruited 20 second graders (12 girls and 8 boys; mean age = 7 years and 8 months, $SD =$
236 4 months) and 19 fifth graders (9 girls and 10 boys; mean age = 11 years and 1 month, $SD = 1$
237 year and 1 month) from schools in the Poitiers area in France. We also included 20 adults in
238 this experiment (16 women and 4 men; mean age = 25 years and 4 months, $SD = 9$ years and
239 10 months). None of the participants had any known motor, developmental or learning
240 disorders at the time of testing. Written informed consent was obtained from the children's
241 parents prior the study. Participation was completely voluntary for both children and adults.

242 2.2. Experimental Tasks

243 In this experiment, participants completed two writing tasks: a letter-handwriting task
244 and a pseudoword-handwriting task. In the letter-handwriting task, participants were asked to
245 write five isolated cursive letters (*a, o, l, m, p*). We used the same letters as Vinter and
246 Chartrel (2006), who chose these items because they varied according their projection axis
247 (horizontal for *m* and vertical for *l* and *p*), aperture (open for *m* and closed for *a* and *o*) and
248 extension (low for *a* and *o* and high for *m* and *p*). In the pseudoword-handwriting task,
249 participants were invited to write three pseudowords that contained the same letters as those
250 used in the first task: *lamopa, molopa, palomo*.

251 In both tasks, participants had to write each letter and pseudoword in their usual
252 handwriting (usual letter size and writing speed). Each letter or pseudoword was displayed on
253 the tablet screen and disappeared as soon as the pen touched the screen (Fig. 1). Once the item
254 had been written, participants pressed the pen tip on a red square marked *Fin* in the bottom
255 righthand corner of the screen.

256

257

Insert Fig. 1

258

259 **2.3. Materials**

260 Writing performances were recorded using an LCD digitizing tablet (a 21-inch
261 Wacom Cintiq 21UX) connected to a laptop computer (Apple MacBook) piloted by Eye and
262 Pen software® (Alamargot, Chesnet, Dansac, & Ros, 2006; Chesnet & Alamargot, 2005).
263 Participants wrote on a plastic board placed on top of the tablet screen using a pen (Wacom
264 InkPen) with a plastic tip (no ink). We used the Eye and Pen software to (i) record the
265 position and state of the pen tip (with or without pressure) on the plastic board in real time,
266 (ii) manage the display of each item to be written, as well as the visual (letter and pseudoword
267 formation) feedback displayed on the screen, and (iii) provide velocity and kinematic
268 (pressure exerted on the pen, pen movement speed, pause duration, distance covered by the
269 pen) at the end of the task.

270 As the plastic board was transparent, participants could see their handwriting in the
271 normal vision condition (*vision* condition). In the *no vision* condition, a shield was used to
272 prevent participants from receiving visual feedback about their hand and what they were
273 writing. This shield was opaque, and measured 23 cm high and 50 cm long. It was positioned
274 just above the participant's hand, such that both hand movements and handwriting were
275 hidden from view. In order to manipulate the *friction*, one side of the plastic board was
276 smooth and the other side was granular. To assess the friction between the pen and the two
277 writing surfaces, we used the same experimental set-up as in the study by Alamargot and
278 Morin (2015). This consisted of an articulated arm that kept the pen tip on the writing surface
279 and constrained its path (see also Wann & Nimmo-Smith, 199). The translational force
280 exerted on the pen to move it was generated by a 40-g load, while the pressure exerted on the

281 tip was controlled by adding a 20-g weight to the pen. Measures of pen movement speed (for
282 20 cm of translational motion) were repeated in the two texture conditions. Results confirmed
283 a difference in pen movement speed induced by the different degrees of friction on the two
284 sides of the plastic board (smooth side: 7.52 cm/s; granular side: 3.60 cm/s; $p < .001$). It
285 should be noted that, according to Alamargot and Morin (2015), pen movement speed on a 80
286 g/m paper surface is 5.70 cm/s, when measured under the same conditions.

287 **2.4. Procedure**

288 Participants performed the two handwriting tasks individually in a quiet room. All
289 participants performed these two handwriting tasks in all four conditions: smooth or granular
290 side of the plastic board (manipulation of *surface friction*); with normal vision or behind a
291 shield that hid the hand and handwriting from direct view (manipulation of *vision*). Thus, each
292 age group (second graders, fifth graders and adults) were exposed to all four combinations of
293 sensory input (vision/granular surface, vision/ smooth surface, no vision/granular surface, no
294 vision/ smooth surface) during the handwriting tasks. For each participant, order of the tasks
295 was alternated from one sensory situation to the other. A short training session was
296 administered before each sensory situation, during which participants were asked to write two
297 letters (*n* and *e*) and a pseudoword (*fenu*). This training session was intended to familiarize
298 participants with each new handwriting condition. All participants started with the most
299 common handwriting condition (i.e., vision/granular surface). The order of the other three
300 sensory situations (vision/smooth surface, no vision/granular surface, no vision/smooth
301 surface) was counterbalanced across participants. No time limit was imposed on participants.
302 For each handwriting task, the items (letters or pseudowords) were presented in a random
303 order across participants.

304 **2.5. Data Analysis**

305 We began by investigating handwriting performances with an analysis of letter legibility. Two
306 raters determined whether each letter that was produced was legible or not, using the
307 Evaluation Tool of Children's Handwriting (ETCH; Amundson, 1995; see also Alamargot et
308 al., 2014). According to Evaluation Tool criteria (Amundson, 1995), a letter is non-legible if
309 it is not quickly recognizable out of context and at first glance, is poorly formed, distorted,
310 reversed or greatly rotated, is confused with another letter or numeral, has additional or
311 missing parts, is sloppy or intentionally hatched, overlaps with another letter, or is not
312 proportional. Based on these criteria, each correctly formed letter was scored one point in
313 both the letter-handwriting task (total of 20 letters produced in isolation) and the pseudoword-
314 handwriting task (6 letters per item). A score of 0 meant that the letter was not legible.

315 To test the reliability of this analysis of legibility for the two handwriting tasks, we ran
316 Student's *t* tests and calculated Pearson correlation coefficients between the scores of the two
317 raters. For the 20 isolated letters in the letter-handwriting task, results show no significant
318 difference between the two raters' scores (Rater 1: $M = 13.33$, $SD = 2.78$; Rater 2: $M = 13.5$,
319 $SD = 3.17$; $p > .92$), and the coefficient of correlation for the two scored series was high ($r =$
320 $.95$). For the pseudoword-handwriting task, the analysis of coding reliability was also
321 satisfactory, as there was no significant difference between the two raters' scores regarding
322 the number of legible letters per item (Rater 1: $M = 4.37$, $SD = 0.32$; Rater 2: $M = 4.42$, $SD =$
323 0.39 ; $p > .83$), and the coefficient of correlation was high ($r = .96$). A similar analysis carried
324 out for all four conditions-pseudowords as well as isolated letters - also indicated good coding
325 reliability, with a minimum correlation coefficient of $r = .84$, $p > .71$. This letter legibility
326 assessment was complemented by an analysis of handwriting kinematics for all the letters and
327 pseudowords that were produced, whatever their legibility. We recorded the following
328 kinematic variables: *letter size* in cm (pen trajectory length/number of letters produced); *pen*
329 *speed* in cm/s (mean speed of pen movements between two pauses); *pen pressure* on the

330 plastic board's surface; and *duration of pen pauses* in ms (a pause had to last at least 30 ms).
331 Duration of pen pauses was analysed in the pseudoword-handwriting task, but not in the
332 letter-handwriting task, as only 12% of participants paused during the production of isolated
333 letters.

334 **3. Results**

335 Descriptive statistics about handwriting kinematics are summarized in Tables 1 and 2.
336 We analysed the data with repeated-measures analyses of variance (ANOVAs). More
337 specifically, for each task, we ran a $3 \times 2 \times 2$ repeated-measures ANOVA for each dependent
338 variable, with age group (second graders, fifth graders, and adults) as a between-participants
339 factor, and surface (smooth or granular) and vision (with or without) as within-participants
340 factors. The results of these ANOVAs are provided in Table 3 for the letter-handwriting task,
341 and in Table 4 for the pseudoword-handwriting task. Newman-Keuls tests were performed to
342 assess post hoc differences at a significance threshold that survived Bonferroni correction.

343 **3.1. Letter-Handwriting Task**

344 **3.1.1. Letter legibility**

345 For each participant, we averaged the legibility scores of the five isolated letters. The
346 resulting mean score could vary between 0 and 1. Analysis revealed a significant effect of
347 vision, such that legibility scores were lower when participants had to write without vision (M
348 $= 0.70$, $SD = 0.21$) than with vision ($M = 0.75$, $SD = 0.23$). The main effect of age group
349 tended towards significance, as fifth graders produced fewer legible letters ($M = 0.65$, $SD =$
350 0.23) than second graders ($M = 0.74$, $SD = 0.23$), who produced fewer legible letters than
351 adults ($M = 0.77$, $SD = 0.19$).

352 **3.1.2. Handwriting kinematics**

353 *Letter size*

354 We found a significant effect of vision, such that the pen travelled a greater distance to
355 form a letter when participants could not see either their hand or their handwriting ($M = 5.51$,
356 $SD = 1.66$) than when they could ($M = 4.8$, $SD = 1.49$). The interaction between vision and
357 surface did not quite reach significance, $F(1, 56) = 3.08$, $p = .08$ (see Fig. 2.).

358 *Pen speed*

359 Analysis showed a significant effect of surface, such that the pen moved faster across
360 the granular surface ($M = 5.21$, $SD = 2.71$) than across the smooth one ($M = 4.84$, $SD = 2.13$).
361 Furthermore, the effect of vision was significant, such that the velocity of the pen was greater
362 when participants could not watch their hand and their handwriting ($M = 5.36$, $SD = 2.60$)
363 than when they could ($M = 4.69$, $SD = 2.23$). As expected, this effect varied according to age
364 group, as revealed by the interaction between age group and vision. The pen moved faster in
365 the no vision condition than in the vision one, but only for second graders (1.25 cm/s
366 difference, $p < .002$). Finally, the interaction between vision and surface was significant. As
367 we can see in Figure 2, pen velocity was greater in the no vision condition, especially when
368 participants had to write on the smooth surface (1.05 cm/s difference between vision and no
369 vision conditions for the smooth surface, $p < .001$; 0.28 cm/s difference between vision and
370 no vision conditions for the granular surface, $p = .07$).

371 *Pen pressure*

372 The effect of vision tended towards significance such that greater pressure was exerted by
373 the pen in the no vision condition ($M = 931$, $SD = 76$) than in the vision condition ($M = 922$,
374 $SD = 80$).

375 **Insert Table 1**

376 **Insert Table 3**

377

378 **3.2.Pseudoword-Handwriting Task**

379 **3.2.1 Letter legibility**

380 For each participant, we calculated the mean legibility score for each of the three
381 pseudowords, by averaging the scores for the letters they consisted of. This yielded a mean
382 score of between 0 and 6 for each item in this task. The legibility score was higher when
383 participants could see their hand and their handwriting ($M = 4.85, SD = 0.68$) than when they
384 could not ($M = 3.97, SD = 0.82$), as reflected by the significant effect of vision.
385 Unsurprisingly, there was a significant interaction between vision and age group. The
386 difference in legibility scores between the vision and no vision conditions was more
387 pronounced in second graders (1.31 difference, $p < .001$) than in either fifth graders (0.70
388 difference, $p < .001$) or adults (0.63 difference, $p < .001$). As expected, the Vision x Surface
389 interaction was significant. Legibility scores were lower for the smooth surface than for the
390 granular surface, but only in the no vision condition (0.20 difference, $p = .024$).

391 **3.2.2 Handwriting kinematics**

392 *Letter size*

393 Analysis revealed a significant effect of age group. The distance travelled by the pen
394 to form a letter was greater for second graders ($M = 4.05, SD = 1.49$) than for adults ($M =$
395 $3.77, SD = 1.21$), and greater for adults than for fifth graders ($M = 3.14, SD = 0.91$). We also
396 observed a significant effect of vision, such that letter size was greater when participants
397 could not see their hand and their handwriting ($M = 3.98, SD = 1.32$) than when they could (M
398 $= 3.35, SD = 1.16$). As expected, analysis indicated a significant interaction between age
399 group and vision. The main effect of vision was significant in second graders (1.07 cm
400 difference, $p < .001$) and in fifth graders (.50 cm difference, $p = .008$), but not in adults (.31
401 cm difference, $p = .09$). There was also a significant interaction between age group and
402 surface. Letter size was greater when fifth graders wrote on the smooth surface compared with
403 the granular surface (.32 cm difference, $p < .001$). No significant difference was observed

404 between the smooth and granular surfaces in either the second graders (.03 cm difference, $p >$
405 .70) or the adults (.04 cm difference, $p > .60$). Finally, as expected, and as demonstrated by
406 the significant interaction between vision and surface, mean letter size was modified by
407 surface, but only in the no vision condition (.18 cm difference between smooth and granular
408 surfaces, $p < .01$) (Fig. 2).

409 *Pen speed*

410 Concerning mean velocity per letter, there was a significant effect of age group, as
411 velocity increased with age (second graders: $M = 3.34$, $SD = 1.48$; fifth graders: $M = 4.01$, SD
412 $= 1.49$; adults: $M = 5.12$, $SD = 1.83$). The main effect of vision was also significant. Mean
413 velocity was greater in the no vision condition ($M = 4.38$, $SD = 1.82$) than in the vision
414 condition ($M = 3.94$, $SD = 1.70$). As expected, there was a significant interaction between
415 vision and surface (see Fig. 2). Pen velocity increased in the no vision condition, especially
416 when participants had to write on the smooth surface (0.64 cm/s difference between vision
417 and no vision conditions for the smooth surface, $p < .001$; 0.23 cm/s difference between vision
418 and no vision conditions for the granular surface; $p = .048$, *ns* after Bonferroni correction).

419 **Insert Fig. 2**

420 *Pen pressure*

421 Analysis only indicated a trend towards significance for the effect of vision, such that
422 less force was exerted on the pen when participants could see their hand and what they had
423 written ($M = 940$, $SD = 73$) than when they could not ($M = 950$, $SD = 85$). No other effect or
424 interaction were observed.

425 *Pause duration*

426 There was a significant effect of age group, such that mean pause duration decreased
427 with age (second graders: $M = 1963$, $SD = 1654$; fifth graders: $M = 1053$, $SD = 887$; adults: M
428 $= 765$, $SD = 787$). Furthermore, pauses were longer in the vision condition ($M = 1508$, $SD =$

429 1488) than in the no vision condition ($M = 1020$, $SD = 983$), as reflected by the significant
430 effect of vision. No other significant results were observed.

431

432 **Insert Table 2**

433 **Insert Table 4**

434

435 **4. Discussion**

436 The present study was designed to examine the compensatory role of visual
437 information when children and adults have to write on a tablet screen, by unravelling the
438 respective contributions of visual and proprioceptive feedback during two handwriting tasks.
439 To this end, we compared the handwriting performances of three age groups (second graders,
440 fifth graders, and adults). Participants were asked to write single letters and pseudowords in
441 four different conditions: on a smooth or granular surface with or without vision. We tested
442 two assumptions based on literature findings: 1) disturbances in handwriting kinematics, and
443 possibly also in letter legibility, should be observed with a lower friction surface, especially
444 when visual information is not available; 2) the nonavailability of visual information and the
445 reduction in proprioceptive information induced by a smooth tablet screen should disturb
446 children's handwriting performances more than those of adults.

447

448 **4.1. Handwriting on a Smooth Surface: Using Visual Information to Compensate for** 449 **the Reduction in Proprioceptive Information**

450 Results confirmed our first hypothesis, as disturbances of handwriting on a smooth
451 versus granular surface were more pronounced when visual information was withdrawn.
452 Concerning pseudoword items, these disturbances concerned both the process and product of
453 handwriting. More specifically, in the absence of vision, pen speed and pen trajectory length

454 increased more when participants produced pseudowords on the lower friction surface. These
455 results extend those of Alamargot and Morin (2015) for children and adolescents handwriting
456 on a low-friction surface. Participants compensated for the reduced proprioceptive
457 information from the smooth writing surface by amplifying their movement and increasing
458 their pen velocity, especially when visual feedback was not available. However, this online
459 adaptation of movement kinematics was not sufficient, as the letters were less legible when
460 participants wrote on the smooth surface rather than the granular surface when they could not
461 see what they had just written. Concerning the production of isolated letters, the only
462 significant interaction between vision and surface concerned the velocity of the pen: pen
463 speed increased when participants had to write on the smooth surface, especially when no
464 visual feedback was available. Disturbances were therefore smaller during the writing of
465 letters than of pseudowords. This may be related to the degree of sequencing of the subunits
466 that made up each item, which was greater for the pseudowords than for the isolated letters.
467 The order of the subunits making up each isolated letter could mostly be determined in
468 advance, whereas the order of the subunits making up the pseudowords could not be fully
469 specified before the onset of movement, and consequently relied more heavily on sensory
470 feedback.

471 Taken together, these results corroborate previous data suggesting that both vision and
472 proprioception contribute to the control of handwriting (for a review, see Danna & Velay,
473 2015). Our results suggest that participants compensated for the decrease in proprioceptive
474 feedback induced by the lower friction surface by relying more on visual information. Vision
475 is thought to have two distinct functions in handwriting production (Alamargot, Chesnet, &
476 Caporossi, 2012; Smyth & Silvers, 1987). First, *exproprioceptive control* refers to the spatial
477 organization of handwriting and is involved in the maintenance of spatial position within the
478 writing space. The second role of vision concerns the accurate formation of movement

479 sequences and is probably shared with the articular *proprioceptive system*. Controlling the
480 kinematics and dynamics of handwriting requires the integration of effector location and
481 position. As indicated by Hepp-Reymond et al. (2009), this process needs constant updating
482 by proprioceptive feedback. In the absence of vision, the reduction in proprioception induced
483 by the smooth surface may impair this updating mechanism, which in turn may cause an
484 increase in letter size and pen speed, as well as a reduction in letter legibility for sequences of
485 letters (i.e., pseudowords).

486 Furthermore, the interaction between vision and surface was not modulated by the age
487 of participants. Thus, similar compensation mechanisms were used whatever the participants'
488 age, with adults and children alike using vision to compensate for the reduction in
489 proprioception induced by the smooth writing surface.

490 **4.2. Changes in Handwriting Performances and Use of Sensory Feedback with Age**

491 When we compared the handwriting performances of the three age groups (second
492 graders, fifth graders and adults), we found changes in both the handwriting product and the
493 handwriting process (kinematic parameters). Concerning the handwriting product, when
494 participants had to form isolated letters, legibility tended to decrease between Grades Two
495 and Five, but then increased between Grade Five and adulthood. This result contrasted with
496 previous studies, which had revealed an improvement in handwriting quality between the ages
497 of 6 and 8 years (Blöte & Hamstra-Bletz, 1991; Graham, Berninger, Weintraub, & Schafer,
498 1998; Overvelde & Hulstijn, 2011; Vinter & Zesiger, 2007). However, our results support
499 those of Mojet (1991), who reported a nonmonotonic change in legibility across childhood. In
500 our study, the decline in legibility between second and fifth grade could be related to the wide
501 variability in handwriting performances (particularly regarding speed and legibility) that is
502 observed in younger writers before motor programme acquisition (Feder, Majnemer,
503 Bourbonnais, Blaynet, & Morin, 2007; Graham, Struck, Santoro, & Berninger, 2006).

504 Furthermore, this nonmonotonic development is in line with the idea of a first phase in which
505 young writers concentrate on the academic requirements of legibility, followed by a second
506 phase in which they focus on speed requirements, leading them to depart from the standard
507 letter shapes (Ajuriaguerra, 1971).

508 Concerning the handwriting process, more modifications were observed in the
509 pseudoword-handwriting task compared to the letter-handwriting task. Mean velocity
510 increased and pause duration decreased with age, suggesting an improvement in fluency
511 between 7-8 years of age and adulthood. These results are consistent with previous studies
512 that revealed an overall improvement in velocity and fluency with age (Chartrel & Vinter,
513 2006, 2008; Meulenbroek & Van Galen, 1988), and suggest that the size of the subunits
514 contained in motor programmes increases with practice (Hulstijn & Van Galen, 1983; Portier,
515 Van Galen, & Meulenbroek, 1990; Teulings, Mullins, & Stelmach, 1986), from single strokes
516 to whole letters. After even more practice, the extent of the prepared movement may cover
517 combinations of letters. Furthermore, a nonmonotonic change was observed for letter size in
518 the pseudoword-handwriting task. Pen trajectory length decreased between Grades Two and
519 Five, then increased between Grade Five and adulthood. This result corroborates the data
520 reported by Chartrel and Vinter (2006).

521 The modifications we observed in these kinematic parameters may be explained by the
522 switch from a retroactive mode of motor control at age 7 years, based on the use of sensory
523 feedback, to a more proactive mode of control at age 9-10 years, based mainly on the
524 execution of motor programmes. Our results support this interpretation: the reduction in
525 sensory feedback (notably visual) affected handwriting performances more in younger
526 participants than in older ones. Concerning the production of isolated letters, in the absence of
527 vision, mean velocity increased in second graders, whereas this parameter was not modified
528 by the absence of visual feedback in fifth graders and adults. Concerning pseudoword

529 production, letters were larger for second graders and, to a lesser extent, fifth graders, when
530 visual feedback was not available, and the younger the participants, the less legible the letters.
531 Taken together, these results are generally consistent with those of Chartrel and Vinter
532 (2006), and suggest growing independence with age from visual feedback for the control of
533 handwriting. To conclude, visual information is crucial for younger writers who do not yet
534 possess complete representations of letter shapes and thus predominantly use visual
535 information to guide their handwriting movements. As indicated by Chartrel and Vinter
536 (2006), depriving children of visual feedback modifies the movement parameters. Letter size,
537 for instance, increases in order to maximize proprioceptive information. With practice and
538 experience, children gradually construct motor programmes that contain the instructions
539 needed for motor control and allow them to dispense with these sensory signals.

540 The effect of surface was only weakly modulated by participants' age. The only
541 significant interaction between age and surface concerned letter size for the production of
542 pseudowords. Fifth graders enlarged their movement when they wrote on the lower friction
543 surface, whereas no difference between the smooth and granular surfaces was observed in
544 second graders and adults. The age of 9-10 years is traditionally described as a transitional
545 period characterized by the formation of motor programmes. Several studies have indicated
546 that the gradual improvement in predictive motor control during childhood is tied to an
547 increase in the ability to integrate proprioceptive signals with visual feedback at around 9-10
548 years of age (Chicoine et al., 1992; von Hofsten & Rösblad, 1988). This increased ability may
549 have led the fifth graders to exaggerate their movements in order to rely more on
550 proprioceptive signals when no visual feedback was available.

551 Finally, our results suggest that even if the proactive mode limits recourse to sensory
552 feedback, the latter continues to contribute to the control of movement even in adults.
553 Participants of all ages wrote larger letters when they could not see their hand in the letter-

554 handwriting task. This increase in size could serve to maximize the amount of proprioceptive
555 information available to participants during the handwriting task. Concerning the pen
556 pressure, although the effect of vision failed to attain significance Furthermore, our results
557 concerning the pen pressure are in line with the study of Chartrel and Vinter (2006) showing
558 that participants press down harder on the pen in the absence of vision. However, in our
559 experiment, the effect of vision failed to reach statistical significance in both the letter- and
560 pseudoword-handwriting tasks. Therefore, further studies are needed to confirm that writers
561 compensate for the absence of visual information by pressing down harder on the pen.
562 Finally, participants made shorter pauses when they could not see their hand and their
563 handwriting. This could be a result of the overall increase in mean velocity in the no vision
564 condition. Chartrel and Vinter (2008) showed that imposing spatiotemporal constraints on
565 handwriting movements leads writers to increase their spontaneous writing speed and allows
566 for more fluent handwriting movements.

567 **4.3. Limitations**

568 Our study afforded a better understanding of the respective roles of visual and proprioceptive
569 feedback during handwriting, but had several limitations. In the no vision condition,
570 participants were prevented from watching their hand and their handwriting, but were not
571 fully deprived of visual feedback during the task, as there were other sources of visual
572 information around them. One might assume that the online adaptation of movement
573 kinematics would have been different, if participants had been asked to close their eyes
574 (complete isolation from visual information) while performing the tasks, especially in the case
575 of the fifth graders, who were at a stage where proprioceptive signals start to be integrated
576 with visual feedback during motor control. However, as the visual information available in
577 our no vision condition did not really concern the characteristics of the handwriting, we do

578 not believe that this would have been the case. Nevertheless, further studies should explore
579 this issue in the future.

580 Finally, unlike previous studies that explored the impact of writing surface on handwriting
581 kinematics (Alamargot & Morin, 2015; Gerth, Dolk et al., 2016; Gerth, Klassert et al., 2016),
582 we observed very few main effects of surface in the present research. These divergent results
583 may be due to methodological differences in the constraints imposed on participants during
584 the handwriting tasks. In the previous studies, participants had to write their names, surnames
585 and letters of the alphabet on lines in predefined writing areas (Alamargot & Morin, 2015) or
586 write a sentence on lines and copy geometric forms in predefined writing spaces (Gerth, Dolk
587 et al., 2016; Gerth, Klassert et al., 2016). Participants therefore had to take these specific
588 constraints into account in order to control and accurately adjust their handwriting
589 movements. In the present study, no such spatial constraints were imposed on participants. As
590 indicated by Gerth and colleagues, the degree of adaptation is dependent on the task's
591 graphomotor demands. Our findings can therefore only be generalized to tasks that do not
592 impose strong spatial constraints during handwriting.

593 **5. Conclusion**

594 To conclude, this study contributes to a better understanding of the respective
595 contributions of visual and proprioceptive feedback during handwriting development.

596 Participants compensated for the decrease in proprioceptive feedback induced by a smooth
597 writing surface by relying more heavily on visual information. This compensation mechanism
598 may have a cognitive cost for performances at a higher processing level that should be
599 investigated further in the future. This issue is all the more important as lower-level
600 handwriting processes, such as graphomotor execution, have an influence on higher-level
601 processes, such as composition or spelling (Graham, Berninger, Abbott, Abbott, & Whitaker,
602 1997; Morin, Lavoie, & Montesinos, 2012; Pontart et al., 2013). In fact, lower-level processes

603 need to be mastered first in handwriting learning, as they require considerable attentional
604 resources. Therefore, further studies are needed to investigate the impact of handwriting on a
605 tablet computer on orthographic and composition skills. This question of the link between
606 new handwriting media and higher-level processes is all the more important that these media
607 are increasingly being used in schools for a variety of tasks. Research has demonstrated that
608 these new technologies can be used to deliver individualized writing exercises (Girard et al.,
609 2017; Jolly et al., 2013; Patchan & Puranik, 2016). In accordance with previous data for
610 adults (Alamargot & Morin, 2015; Gerth, Dolk et al., 2016; Gerth, Klassert et al., 2016), our
611 results show that, by modifying the usual writing conditions, the use of these tools lead to
612 disturbances in graphomotor execution. Consequently, our results will serve as useful pointers
613 for improving the design of this tool for children by, say, increasing the screen surface's
614 degree of friction.

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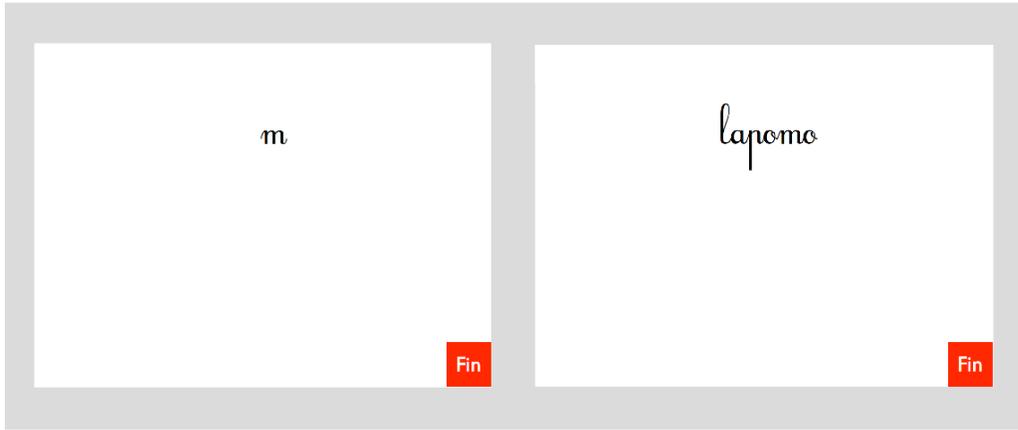


Fig. 1. Example of the information displayed on the tablet screen for the letter-handwriting task (left) and the pseudoword-handwriting task (right).

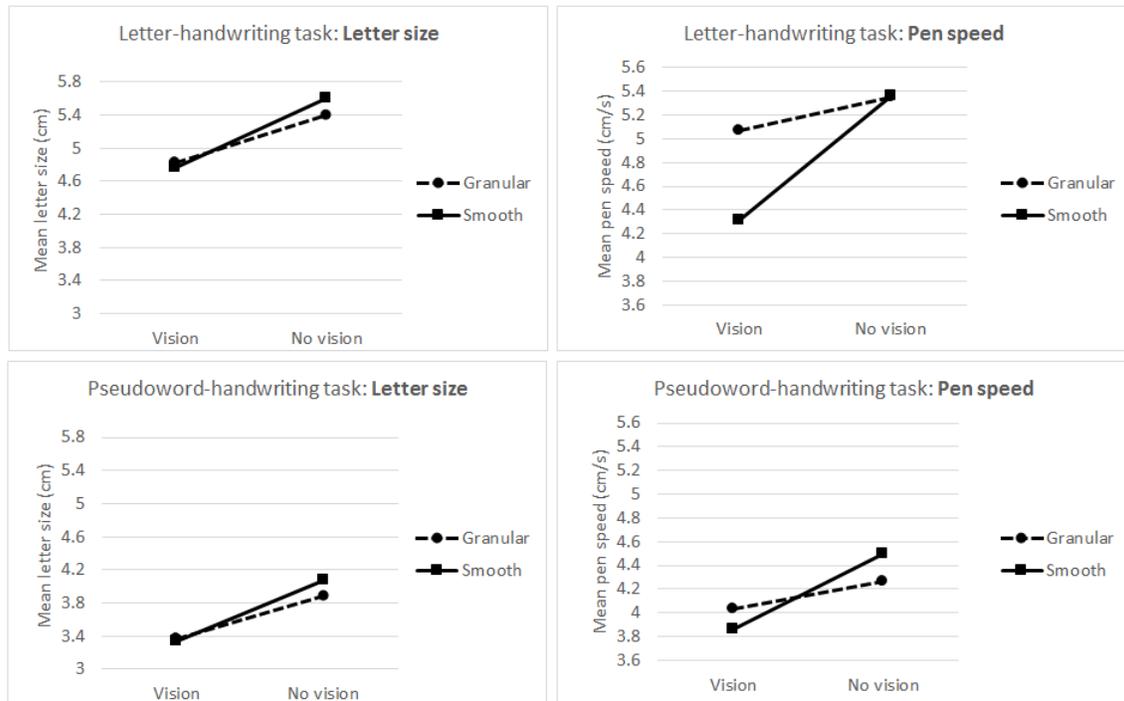


Fig. 2. Mean letter size (cm) in letter-handwriting task (top left) and pseudoword-handwriting task (top right), and mean pen speed (cm/s) in letter-handwriting task (below left) and pseudoword-handwriting task (below right) for the two vision conditions (vision and no vision) and the two surface conditions (smooth and granular).

Table 1

Handwriting kinematics in letter-handwriting task: mean (*standard deviation*) letter size (cm), pen speed (cm/s), pen pressure and legibility score according to age group (second graders, fifth graders or adults), surface (smooth or granular) and vision (with or without vision).

		Granular surface		Smooth surface	
		Vision	No vision	Vision	No vision
Letter size (cm)	Second graders	6.15 (1.64)	5.97 (2.10)	5.06 (1.49)	5.14 (1.57)
	Fifth graders	4.26 (1.25)	4.80 (1.27)	4.48 (1.50)	5.13 (1.45)
	Adults	5.05 (1.64)	5.41 (1.59)	4.76 (1.45)	5.53 (1.59)
Pen speed (cm/s)	Second graders	4.23 (1.93)	5.35 (3.47)	3.64 (1.32)	4.23 (1.93)
	Fifth graders	4.98 (1.96)	4.80 (1.95)	4.11 (1.22)	5.18 (2.02)
	Adults	6.45 (3.20)	5.88 (2.87)	5.18 (2.13)	5.88 (2.29)
Pen pressure	Second graders	910 (90)	918 (98)	921 (88)	927 (71)
	Fifth graders	918 (78)	924 (77)	907 (83)	941 (59)
	Adults	938 (78)	936 (81)	938 (67)	941 (71)
Legibility score	Second graders	0.76 (0.28)	0.73 (0.19)	0.79 (0.22)	0.68 (0.22)
	Fifth graders	0.68 (0.24)	0.64 (0.24)	0.65 (0.26)	0.63 (0.19)
	Adults	0.81 (0.14)	0.75 (0.25)	0.78 (0.19)	0.75 (0.17)

Table 2

Handwriting kinematics in pseudoword-handwriting task: mean (*standard deviation*) letter size (cm), pen speed (cm/s), pen pressure, pause duration (ms) and legibility score according to age group (second graders, fifth graders or adults), surface (smooth or granular) and vision (with or without vision).

		Granular surface		Smooth surface	
		Vision	No vision	Vision	No vision
Letter size (cm)	Second graders	3.57 (1.29)	4.56 (1.65)	3.48 (1.31)	4.61 (1.37)
	Fifth graders	2.76 (0.67)	3.21 (0.87)	3.04 (0.90)	3.56 (1.01)
	Adults	3.74 (1.30)	3.85 (1.17)	3.50 (1.18)	4.00 (1.73)
Pen speed (cm/s)	Second graders	3.04 (1.39)	3.70 (1.77)	2.85 (1.18)	3.76 (1.42)
	Fifth graders	3.74 (1.08)	4.03 (1.62)	3.83 (1.09)	4.45 (2.01)
	Adults	5.29 (2.05)	5.03 (1.77)	4.88 (1.72)	5.29 (1.87)
Pen pressure	Second graders	928 (83)	942 (99)	935 (86)	946 (129)
	Fifth graders	929(72)	938 (68)	941 (61)	959 (59)
	Adults	952 (71)	961 (60)	953 (66)	956 (79)
Pause duration (ms)	Second graders	911 (852)	486 (408)	1032 (837)	630 (885)
	Fifth graders	1286 (889)	873 (771)	1216 (1154)	839 (625)
	Adults	952 (71)	961 (60)	953 (66)	956 (79)
Legibility score	Second graders	4.83 (0.71)	3.82 (0.62)	5.12 (0.73)	3.52 (0.81)
	Fifth graders	4.75 (0.66)	4.19 (0.77)	4.81 (0.57)	3.96 (0.67)
	Adults	4.73 (0.76)	4.20 (0.94)	4.85 (0.63)	4.13 (0.95)

Table 3

Significant and tendencial results of ANOVA for letter-handwriting task

Handwriting Measures	Source of variance	Df	F values	P values	η^2 values
Legibility	Main Effect				
	Vision	1	5.21	.026	.09
	Age	2	2.96	<.06	.10
Letter size	Main Effect				
	Vision	1	27.8	<.001	.33
Pen speed	Main Effect				
	Vision	1	13.49	<.001	.19
	Surface	1	8.22	<.01	.13
	Two-way interaction				
	Vision x Age	2	3.58	.035	.11
	Vision x Surface	1	12.92	<.001	.18
Pen Pressure	Main Effect				
	Vision	1	3.78	.057	.06

Table 4

Significant and tendencial results of ANOVA for pseudoword-handwriting task

Handwriting Measures	Source of variance	Df	F values	P values	η^2 values
Legibility	Main Effect				
	Vision	1	148.06	< .001	.73
	Two-way interaction				
	Vision x Age	2	9.07	< .001	.24
	Vision x Surface	1	8.29	< .01	.13
Letter size	Main Effect				
	Age	2	3.47	.038	.11
	Vision	1	36.87	< .001	.40
	Two-way interaction				
	Vision x Age	2	5.08	< .01	.15
	Surface x Age	2	5.6	< .01	.17
	Vision x Surface		4.86	.03	.08
Pen speed	Main Effect				
	Age	2	7.39	< .01	.21
	Vision	1	11.10	< .01	.17
	Two-way interaction				
	Vision x Surface	1	6.58	= .01	.11
Pen Pressure	Main Effect				
	Vision	1	3.58	= .06	.06
Pause duration	Main Effect				
	Age	2	11.70	<.001	.29
	Vision	1	15.04	< .001	.21