Human Movement Science 65 (2019) 30–41

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

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

Jessica Guilbert[a,*], Denis Alamargot[a], Marie-France Morin[b]

[a] *Laboratoire Cognitions Humaine et Artificielle (CHArt – EA 4004), Université Paris-Est, UPEC, 94000 Créteil, France*
[b] *Chaire de Recherche sur l'Apprentissage de la Lecture et de l'ECriture chez le jeune enfant (CREALEC), Faculté d'Education, Université de Sherbrooke, Québec, Canada*

ARTICLE INFO

Keywords:
Handwriting
Vision
Proprioception
Graphomotor execution
Digital tablet
Writing development

ABSTRACT

Tablets are increasingly being used in schools for a variety of handwriting tasks. Given that the control of handwriting relies on both visual and proprioceptive feedback, especially in younger writers, this raises the question of whether the texture of the tablet surface affects graphomotor execution. A series of recent studies found that when the smoothness of a tablet screen modifies proprioceptive feedback, the impact on graphomotor execution varies according to the level of the writer's handwriting skills. However, as the writing on the screen remained visible in these studies, participants may have compensated for the decrease in proprioceptive feedback by relying more heavily on visual information. The aim of the present study was therefore to unravel the respective contributions of different types of sensory feedback during handwriting development and, consequently, the compensatory role of visual information when children and adults have to write on a tablet. To this end, we asked second and fifth graders and adult participants to write letters and pseudowords on a plastic board placed on top of a tablet screen. Participants wrote on either the smooth or the granular side of the plastic board (manipulation of surface friction), and with normal vision or behind a shield that hid the hand and handwriting from direct view (manipulation of vision). Kinematic parameters and legibility were recorded to assess handwriting performances. Results revealed a significant interaction between proprioceptive and visual feedback on letter size, pen speed and legibility, regardless of participants' age. Furthermore, reducing the visual and proprioceptive feedback had a greater effect on the children's handwriting performances than on those of adults. Overall, the present study provides new insight into the contribution of the different types of sensory feedback and their interaction with handwriting development. In addition, our results on the impact of tablet surface on graphomotor execution will serve as useful pointers for improving the design of this tool for children, such as increasing the degree of friction of the screen surface.

* Corresponding author at: Laboratoire CHArt-UPEC – ESPE de l'Académie de Créteil – Université Paris-Est Créteil (UPEC), Site de Bonneuil, rue Jean Macé, 94861 Bonneuil sur Marne Cedex, France.

E-mail addresses: jessica.guilbert@u-pec.fr (J. Guilbert), denis.alamargot@u-pec.fr (D. Alamargot), Marie-France.Morin@USherbrooke.ca (M.-F. Morin).

https://doi.org/10.1016/j.humov.2018.09.001
Received 30 January 2018; Received in revised form 2 September 2018; Accepted 3 September 2018
Available online 12 September 2018
0167-9457/ © 2018 Elsevier B.V. All rights reserved.

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, et al., 2016; Gerth, et al., 2016). Consequently, by modifying the usual writing conditions, these new media may make it more difficult for writers to perform their handwriting movements, especially unskilled writers, who control their movements differently from experienced writers.

1.2. Use of sensory feedback during handwriting development

The acquisition of handwriting skills is characterized by a nonlinear improvement in both handwriting legibility, which considers the writing product, and kinematics (writing process), which provides information on the motor control mechanisms (Meulenbroek & Van Galen, 1988; for a review, see Palmis, Danna, Velay, & Longcamp, 2017). Between 7 and 10 years, a transition takes place that has been interpreted as a shift from the online control of movement, based on sensory feedback (retroactive control), to predictive motor control, based mainly on the execution of motor programmes (proactive control) (Meulenbroek & Van Galen, 1988; Zesiger, Deonna, & Mayor, 2000). Before the age of 10 years, writing movement is slow and dysfluent, reflecting the extensive use of visual and kinaesthetic feedback, which disrupts the normally smooth execution of letter segments (Meulenbroek & Van Galen, 1988). Young children tend to exert strong pressure on the pen, denoting considerable muscle tension and general motor involvement during handwriting (Zesiger et al., 2000). They also tend to produce large letters, although letter size gradually decreases to meet school requirements, notably between the first and second grades (Charles, Soppelsa, & Albaret, 2004; Chartrel & Vinter, 2008). These kinematic characteristics reveal that young writers have not yet memorized the correct motor patterns and predominantly rely on the use of visual and kinaesthetic feedback for a twofold purpose: controlling step by step the ongoing movements involved in the production of letter shapes (morphokinetic movements) and those responsible for the spatial layout of the letters in the graphic space (topokinetic movements). At around 9–10 years, the motor programmes dedicated to the production of each letter become memorized in long-term memory (Zesiger et al., 2000). Movement velocity, fluency and legibility increase, while handwriting size, pen pressure, and the number and duration of pauses between two segments decrease (Accardo, Genna, & Borean, 2013; Chartrel & Vinter, 2006; Meulenbroek & Van Galen, 1988; Vinter & Chartrel, 2010). This developmental change in kinematic parameters reflects the improvement in predictive motor control. Letter formation is now programmed before the onset of movement. More specifically, once the motor programmes have been retrieved, information about movement parametrization and muscular adjustments is used to update the motor commands, in order to produce the desired letter shapes. The role of sensory feedback is therefore to confirm that everything goes according to plan (Danna & Velay, 2015; Palmis et al., 2017). Although movement components start to be included in motor programmes at around the age of 9–10 years, fluency and speed continue to improve across adolescence (Accardo et al., 2013; Rueckriegel et al., 2008). Furthermore, adolescents gradually learn to strike the best compromises between legibility and speed requirements, depending on the handwriting context (Chartrel & Vinter, 2004).

In sum, less experienced writers, who have not yet stored any motor programmes, predominantly use sensory information to guide their handwriting movements. Thus, when Chartrel and Vinter (2006) explored the impact of withdrawing visual feedback during the execution of cursive letters in 8-, 9-, 10-year-olds and adults, they found that the handwriting performances of the children were far more affected than those of the adults. More specifically, in the children, movement length, movement velocity, and pen pressure all increased in the absence of visual information, whereas only pen pressure increased in adults. According to the authors, these results suggest that children (and, to a much lesser extent, adults) compensate for the absence of visual information by maximizing proprioceptive feedback to guide their movements. In addition to the growing independence from visual feedback for controlling movement, the gradual improvement in predictive motor control during childhood may be the consequence of an increasing ability to process and integrate the different sources of afferent information (notably visual and kinaesthetic) (von Hofsten & Rosblad, 1988). However, the weakness of kinaesthetic acuity observed until at least 7 years of age prevents preschool children from accurately integrating proprioceptive feedback for online control of movement (Bairstow & Laszlo, 1981; Laszlo & Bairstow, 1984). At around 7 years, children begin to make appropriate use of proprioceptive feedback to correct their ongoing movement. However, this source of information cannot be weighed against visual information (Chicoine, Lassonde, & Proteau, 1992; Laszlo & Bairstow, 1984). As indicated by Chicoine et al. (1992) for aiming movement, before 9 years of age, the different sources of afferent signals are processed independently of each other. It is only at around 8–10 years that signals from multiple modalities start to be integrated in a statistically optimal manner, where each sense is weighted in proportion to its relative reliability in a given condition (Gori, Del Viva, Sandini, & Burr, 2008).

The formation of motor programmes means that the control of morphokinetic movement in adults is much less dependent on sensory feedback than it is in children (Chartrel & Vinter, 2006). However, even in adults, motor control cannot be exclusively proactive: sensory information continues to be used for the execution of motor programmes, but in a monitoring function instead of the moment-to-moment regulation of movements exhibited by young writers (Marquardt, Gentz, & Mai 1999; Van Galen, Smyth, Meulenbroek, & Hylkema, 1989). Concerning the role of visual feedback, several studies have shown that deprivation or modification of vision during handwriting leads to writing errors such as additional strokes, especially for letters with repetitive strokes (Smyth & Silvers, 1987; Tamada, 1995) and to increased movement duration (Van Doorn & Keuss, 1992; Van Galen et al., 1989), though not systematically (Smyth & Silvers, 1987). As indicated by Smyth and Silvers (1987), visual feedback may be important for maintaining order in the output sequence. A number of studies have reported that the withdrawal of visual feedback during handwriting has no effect on automatic movement execution (Marquardt, Gentz, & Mai, 1996; Tucha, Tucha, & Lange, 2008). For instance, Marquardt et al. (1996) showed that velocity profiles (number of inversions in velocity) remained unchanged when adults had to write combinations of characters with their eyes closed. Conscious attention to visual feedback has, however, been found to disturb handwriting automaticity. According to Tucha et al. (2008), visual feedback is used not to control the writing movement, but to monitor the spatial features of the handwriting (stroke size, form and positioning of letters). By contrast, proprioceptive feedback is essential for controlling the kinematics and dynamics of handwriting movements, as demonstrated by studies with deafferented patients characterized by the loss of cutaneous and proprioceptive sensation (e.g., Hepp-Reymond, Chakarov, Schulte-Mönting, Huethe, & Kristeva, 2009; Teasdale, et al., 1993). When Hepp-Reymond et al. (2009) asked a deafferented patient to write the word *parallele* with and without visual control, they observed an increase in the number of pen touches and inversions in velocity, and a decrease in mean stroke frequency, revealing a strong impairment in automated behaviour whatever the vision condition. For their part, Teasdale et al. (1993) showed that deafferented patients may compensate for the absence of proprioceptive information by relying more heavily on visual feedback to control the spatial organization of their writing. The role of proprioceptive feedback has also been investigated in healthy individuals by varying the degree of friction with the handwriting surface (Chan & Lee, 2005; Wann & Nimmo-Smith, 1991). The results of these studies revealed that handwriting speed (Chan & Lee, 2005) and pen pressure (Wann & Nimmo-Smith 1991) were modified when adult participants were asked to write on a low-friction surface. As indicated by Alamargot and Morin (2015), experienced writers are sensitive to the kinematics of handwriting movement, and in this situation, use the strategy of increasing frictional force to achieve an input–output dynamic similar to that of a classic writing surface.

1.3. Handwriting on the screen of a tablet computer

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

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

1.4. Overview

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

As many researchers recognize that handwriting is organized hierarchically (Smyth & Silvers, 1987; Tamada, 1995), we administered two handwriting tasks that varied in the degree of sequencing for the items to be written: a letter-handwriting task involving the production of five isolated letters; and a pseudoword-handwriting task involving the production of three different sequences of letters. A motor plan for handwriting can be viewed as a representation of the serial order of the different subunits (e.g., strokes, letters) composing the item to be produced (e.g., letter, word). Thus, writing a word or a pseudoword needs the order of letters or letter combinations to be programmed, while writing a letter needs the order of the strokes to be programmed. The order of an output sequence is not fully determined in advance, but adjusted on the basis of sensory feedback (Smyth & Silvers, 1987), especially when there is a high degree of sequencing.

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

2. Method

2.1. Participants

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

2.2. Experimental tasks

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

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

2.3. Materials

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

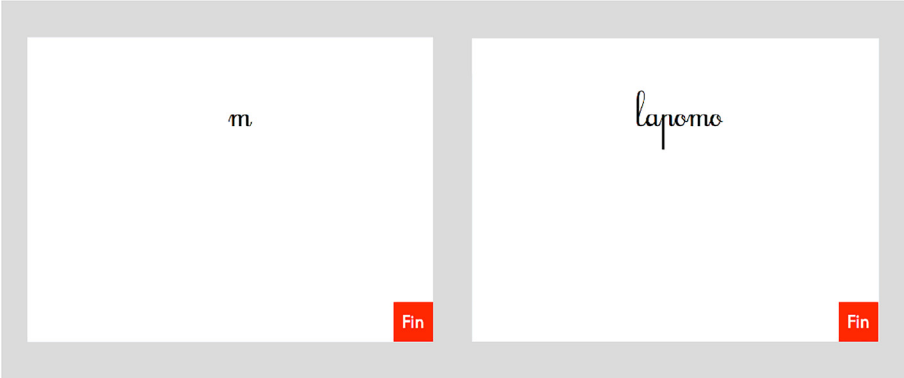

Fig. 1. Example of the information displayed on the tablet screen for the letter-handwriting task (left) and the pseudoword-handwriting task (right).

As the plastic board was transparent, participants could see their handwriting in the normal vision condition (*vision* condition). In the *no vision* condition, a shield was used to prevent participants from receiving visual feedback about their hand and what they were writing. This shield was opaque, and measured 23 cm high and 50 cm long. It was positioned just above the participant's hand, such that both hand movements and handwriting were hidden from view. In order to manipulate the *friction*, one side of the plastic board was smooth and the other side was granular. To assess the friction between the pen and the two writing surfaces, we used the same experimental set-up as in the study by Alamargot and Morin (2015). This consisted of an articulated arm that kept the pen tip on the writing surface and constrained its path (see also Wann & Nimmo-Smith, 199). The translational force exerted on the pen to move it was generated by a 40-g load, while the pressure exerted on the tip was controlled by adding a 20-g weight to the pen. Measures of pen movement speed (for 20 cm of translational motion) were repeated in the two texture conditions. Results confirmed a difference in pen movement speed induced by the different degrees of friction on the two sides of the plastic board (smooth side: 7.52 cm/s; granular side: 3.60 cm/s; $p < .001$). It should be noted that, according to Alamargot and Morin (2015), pen movement speed on a 80 g/m paper surface is 5.70 cm/s, when measured under the same conditions.

2.4. Procedure

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

2.5. Data analysis

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

To test the reliability of this analysis of legibility for the two handwriting tasks, we ran Student's *t* tests and calculated Pearson correlation coefficients between the scores of the two raters. For the 20 isolated letters in the letter-handwriting task, results show no significant difference between the two raters' scores (Rater 1: $M = 13.33$, $SD = 2.78$; Rater 2: $M = 13.5$, $SD = 3.17$; $p > .92$), and the coefficient of correlation for the two scored series was high ($r = 0.95$). For the pseudoword-handwriting task, the analysis of coding reliability was also satisfactory, as there was no significant difference between the two raters' scores regarding the number of legible letters per item (Rater 1: $M = 4.37$, $SD = 0.32$; Rater 2: $M = 4.42$, $SD = 0.39$; $p > .83$), and the coefficient of correlation was high ($r = 0.96$). A similar analysis carried out for all four conditions-pseudowords as well as isolated letters – also indicated good coding reliability, with a minimum correlation coefficient of $r = 0.84$, $p > .71$. This letter legibility assessment was complemented

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)*

by an analysis of handwriting kinematics for all the letters and pseudowords that were produced, whatever their legibility. We recorded the following kinematic variables: *letter size* in cm (pen trajectory length/number of letters produced); *pen speed* in cm/s (mean speed of pen movements between two pauses); *pen pressure* on the plastic board's surface; and *duration of pen pauses* in ms (a pause had to last at least 30 ms). Duration of pen pauses was analysed in the pseudoword-handwriting task, but not in the letter-handwriting task, as only 12% of participants paused during the production of isolated letters.

3. Results

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

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 tendancial 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	0.09
	Age	2	2.96	< .06	0.10
Letter size	Main Effect				
	Vision	1	27.8	< .001	0.33
Pen speed	Main Effect				
	Vision	1	13.49	< .001	0.19
	Surface	1	8.22	< .01	0.13
	Two-way interaction				
	Vision × Age	2	3.58	.035	0.11
	Vision × Surface	1	12.92	< .001	0.18
Pen Pressure	Main Effect				
	Vision	1	3.78	.057	0.06

Table 4
Significant and tendancial 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	0.73
	Two-way interaction				
	Vision × Age	2	9.07	< .001	0.24
	Vision × Surface	1	8.29	< .01	0.13
Letter size	Main Effect				
	Age	2	3.47	.038	0.11
	Vision	1	36.87	< .001	0.40
	Two-way interaction				
	Vision × Age	2	5.08	< .01	0.15
	Surface × Age	2	5.6	< .01	0.17
	Vision × Surface		4.86	.03	0.08
Pen speed	Main Effect				
	Age	2	7.39	< .01	0.21
	Vision	1	11.10	< .01	0.17
	Two-way interaction				
	Vision × Surface	1	6.58	=.01	0.11
Pen Pressure	Main Effect				
	Vision	1	3.58	=.06	0.06
Pause duration	Main Effect				
	Age	2	11.70	< .001	0.29
	Vision	1	15.04	< .001	0.21

3.1. Letter-handwriting task

3.1.1. Letter legibility

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

3.1.2. Handwriting kinematics

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

3.1.2.2. Pen speed. Analysis showed a significant effect of surface, such that the pen moved faster across the granular surface ($M = 5.21$, $SD = 2.71$) than across the smooth one ($M = 4.84$, $SD = 2.13$). Furthermore, the effect of vision was significant, such that the velocity of the pen was greater when participants could not watch their hand and their handwriting ($M = 5.36$, $SD = 2.60$) than

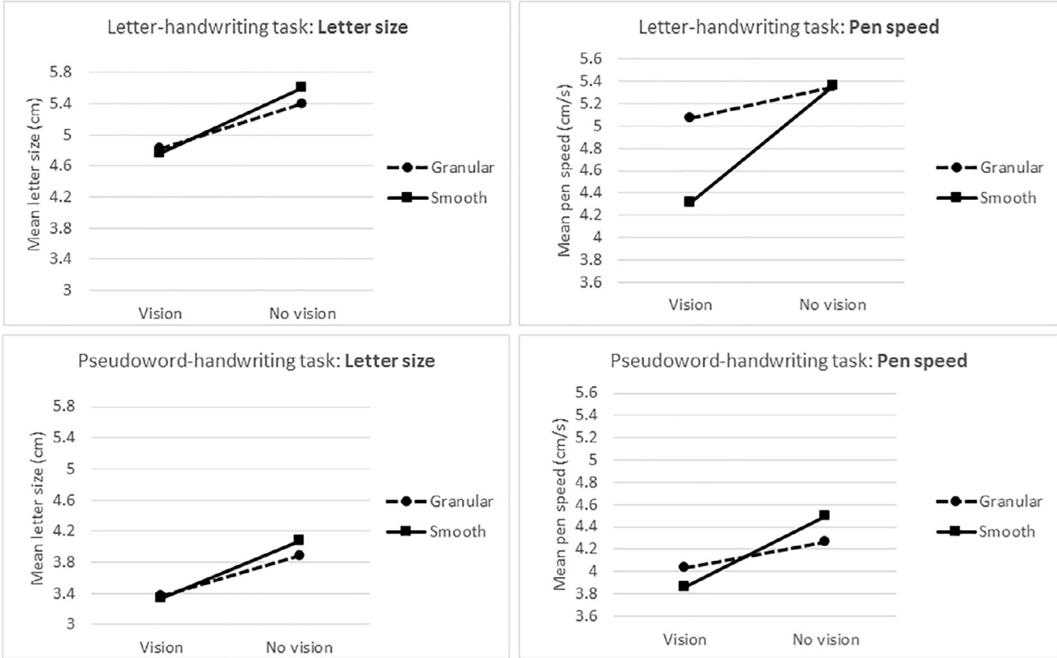

Fig. 2. Mean letter size (cm) in letter-handwriting task (top left) and pseudoword-handwriting task (top right), and mean pen speed (cm/s) in letter-handwriting task (below left) and pseudoword-handwriting task (below right) for the two vision conditions (vision and no vision) and the two surface conditions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

when they could ($M = 4.69$, $SD = 2.23$). As expected, this effect varied according to age group, as revealed by the interaction between age group and vision. The pen moved faster in the no vision condition than in the vision one, but only for second graders (1.25 cm/s difference, $p < .002$). Finally, the interaction between vision and surface was significant. As we can see in Fig. 2, pen velocity was greater in the no vision condition, especially when participants had to write on the smooth surface (1.05 cm/s difference between vision and no vision conditions for the smooth surface, $p < .001$; 0.28 cm/s difference between vision and no vision conditions for the granular surface, $p = .07$).

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

3.2. Pseudoword-handwriting task

3.2.1. Letter legibility

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

3.2.2. Handwriting kinematics

3.2.2.1. Letter size. Analysis revealed a significant effect of age group. The distance travelled by the pen to form a letter was greater for second graders ($M = 4.05$, $SD = 1.49$) than for adults ($M = 3.77$, $SD = 1.21$), and greater for adults than for fifth graders ($M = 3.14$, $SD = 0.91$). We also observed a significant effect of vision, such that letter size was greater when participants could not see their hand and their handwriting ($M = 3.98$, $SD = 1.32$) than when they could ($M = 3.35$, $SD = 1.16$). As expected, analysis indicated a significant interaction between age group and vision. The main effect of vision was significant in second graders (1.07 cm difference, $p < .001$) and in fifth graders (0.50 cm difference, $p = .008$), but not in adults (0.31 cm difference, $p = .09$). There was also a significant interaction between age group and surface. Letter size was greater when fifth graders wrote on the smooth surface compared with the granular surface (0.32 cm difference, $p < .001$). No significant difference was observed between the smooth and granular surfaces in either the second graders (0.03 cm difference, $p > .70$) or the adults (0.04 cm difference, $p > .60$). Finally, as expected, and as demonstrated by the significant interaction between vision and surface, mean letter size was modified by surface, but only in the no vision condition (0.18 cm difference between smooth and granular surfaces, $p < .01$) (Fig. 2).

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

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

3.2.2.4. Pause duration. There was a significant effect of age group, such that mean pause duration decreased with age (second graders: $M = 1963$, $SD = 1654$; fifth graders: $M = 1053$, $SD = 887$; adults: $M = 765$, $SD = 787$). Furthermore, pauses were longer in the vision condition ($M = 1508$, $SD = 1488$) than in the no vision condition ($M = 1020$, $SD = 983$), as reflected by the significant effect of vision. No other significant results were observed.

4. Discussion

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

4.1. Handwriting on a smooth surface: using visual information to compensate for the reduction in proprioceptive information

Results confirmed our first hypothesis, as disturbances of handwriting on a smooth versus granular surface were more pronounced when visual information was withdrawn. Concerning pseudoword items, these disturbances concerned both the process and product of handwriting. More specifically, in the absence of vision, pen speed and pen trajectory length increased more when participants produced pseudowords on the lower friction surface. These results extend those of Alamargot and Morin (2015) for children and adolescents handwriting on a low-friction surface. Participants compensated for the reduced proprioceptive information from the smooth writing surface by amplifying their movement and increasing their pen velocity, especially when visual feedback was not available. However, this online adaptation of movement kinematics was not sufficient, as the letters were less legible when participants wrote on the smooth surface rather than the granular surface when they could not see what they had just written. Concerning the production of isolated letters, the only significant interaction between vision and surface concerned the velocity of the pen: pen speed increased when participants had to write on the smooth surface, especially when no visual feedback was available. Disturbances were therefore smaller during the writing of letters than of pseudowords. This may be related to the degree of sequencing of the subunits that made up each item, which was greater for the pseudowords than for the isolated letters. The order of the subunits making up each isolated letter could mostly be determined in advance, whereas the order of the subunits making up the pseudowords could not be fully specified before the onset of movement, and consequently relied more heavily on sensory feedback.

Taken together, these results corroborate previous data suggesting that both vision and proprioception contribute to the control of handwriting (for a review, see Danna & Velay, 2015). Our results suggest that participants compensated for the decrease in proprioceptive feedback induced by the lower friction surface by relying more on visual information. Vision is thought to have two distinct functions in handwriting production (Alamargot, Chesnet, & Caporossi, 2012; Smyth & Silvers, 1987). First, *exproprioceptive control* refers to the spatial organization of handwriting and is involved in the maintenance of spatial position within the writing space. The second role of vision concerns the accurate formation of movement sequences and is probably shared with the articular *proprioceptive system*. Controlling the kinematics and dynamics of handwriting requires the integration of effector location and position. As indicated by Hepp-Reymond et al. (2009), this process needs constant updating by proprioceptive feedback. In the absence of vision, the reduction in proprioception induced by the smooth surface may impair this updating mechanism, which in turn may cause an increase in letter size and pen speed, as well as a reduction in letter legibility for sequences of letters (i.e., pseudowords).

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

4.2. Changes in handwriting performances and use of sensory feedback with age

When we compared the handwriting performances of the three age groups (second graders, fifth graders and adults), we found changes in both the handwriting product and the handwriting process (kinematic parameters). Concerning the handwriting product, when participants had to form isolated letters, legibility tended to decrease between Grades Two and Five, but then increased between Grade Five and adulthood. This result contrasted with previous studies, which had revealed an improvement in handwriting quality between the ages of 6 and 8 years (Blöte & Hamstra-Bletz, 1991; Graham, Berninger, Weintraub, & Schafer, 1998; Overvelde & Hulstijn, 2011; Vinter & Zesiger, 2007). However, our results support those of Mojet (1991), who reported a nonmonotonic change in legibility across childhood. In our study, the decline in legibility between second and fifth grade could be related to the wide variability in handwriting performances (particularly regarding speed and legibility) that is observed in younger writers before motor programme acquisition (Feder, Majnemer, Bourbonnais, Blaynet, & Morin, 2007; Graham, Struck, Santoro, & Berninger, 2006). Furthermore, this nonmonotonic development is in line with the idea of a first phase in which young writers concentrate on the academic requirements of legibility, followed by a second phase in which they focus on speed requirements, leading them to depart from the standard letter shapes (Ajuriaguerra et al., 1964).

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

The modifications we observed in these kinematic parameters may be explained by the switch from a retroactive mode of motor control at age 7 years, based on the use of sensory feedback, to a more proactive mode of control at age 9–10 years, based mainly on the execution of motor programmes. Our results support this interpretation: the reduction in sensory feedback (notably visual) affected handwriting performances more in younger participants than in older ones. Concerning the production of isolated letters, in the absence of vision, mean velocity increased in second graders, whereas this parameter was not modified by the absence of visual feedback in fifth graders and adults. Concerning pseudoword production, letters were larger for second graders and, to a lesser extent, fifth graders, when visual feedback was not available, and the younger the participants, the less legible the letters. Taken together, these results are generally consistent with those of Chartrel and Vinter (2006), and suggest growing independence with age from visual feedback for the control of handwriting. To conclude, visual information is crucial for younger writers who do not yet possess complete representations of letter shapes and thus predominantly use visual information to guide their handwriting movements. As indicated by Chartrel and Vinter (2006), depriving children of visual feedback modifies the movement parameters. Letter size, for instance, increases in order to maximize proprioceptive information. With practice and experience, children gradually construct motor programmes that contain the instructions needed for motor control and allow them to dispense with these sensory signals.

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

Finally, our results suggest that even if the proactive mode limits recourse to sensory feedback, the latter continues to contribute to the control of movement even in adults. Participants of all ages wrote larger letters when they could not see their hand in the letter-handwriting task. This increase in size could serve to maximize the amount of proprioceptive information available to participants during the handwriting task. Concerning the pen pressure, althought the effect of vision failed to attain significance Furthermore, our results concerning the pen pressure are in line with the study of Chartrel and Vinter (2006) showing that participants press down harder on the pen in the absence of vision. However, in our experiment, the effect of vision failed to reach statistical significance in both the letter- and pseudoword-handwriting tasks. Therefore, further studies are needed to confirm that writers compensate for the absence of visual information by pressing down harder on the pen. Finally, participants made shorter pauses when they could not see their hand and their handwriting. This could be a result of the overall increase in mean velocity in the no vision condition. Chartrel and Vinter (2008) showed that imposing spatiotemporal constraints on handwriting movements leads writers to increase their spontaneous writing speed and allows for more fluent handwriting movements.

4.3. Limitations

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

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

5. Conclusion

To conclude, this study contributes to a better understanding of the respective contributions of visual and proprioceptive feedback during handwriting development. Participants compensated for the decrease in proprioceptive feedback induced by a smooth writing surface by relying more heavily on visual information. This compensation mechanism may have a cognitive cost for performances at a higher processing level that should be investigated further in the future. This issue is all the more important as lower-level handwriting processes, such as graphomotor execution, have an influence on higher-level processes, such as composition or spelling (Graham, Berninger, Abbott, Abbott, & Whitaker, 1997; Morin, Lavoie, & Montesinos, 2012; Pontart et al., 2013). In fact, lower-level processes need to be mastered first in handwriting learning, as they require considerable attentional resources. Therefore, further studies are needed to investigate the impact of handwriting on a tablet computer on orthographic and composition skills. This question of the link between new handwriting media and higher-level processes is all the more important that these media are increasingly being used in schools for a variety of tasks. Research has demonstrated that these new technologies can be used to deliver individualized writing exercises (Girard et al., 2017; Jolly et al., 2013; Patchan & Puranik, 2016). In accordance with previous data for adults (Alamargot & Morin, 2015; Gerth, et al., 2016; Gerth, et al., 2016), our results show that, by modifying the usual writing conditions, the use of these tools lead to disturbances in graphomotor execution. Consequently, our results will serve as useful pointers for improving the design of this tool for children by, say, increasing the screen surface's degree of friction.

References

Accardo, A. A., Genna, M., & Borean, M. (2013). Development, maturation and learning influence on handwriting kinematics. *Human Movement Science, 32*(1), 136–146.

Ajuriaguerra, J., Auzias, M., Coumes, L., Lavondes-Monod, V., Perron, M., & Stambak, M. (1964). L'écriture de l'enfant: Tome 1. L'évolution de l'écriture et ses difficultés. Paris: Delachaux et Niestlé.

Alamargot, D., Chesnet, D., & Caporossi, G. (2012). Using eye and pen movements to study the writing process. In M. Fayol, D. Alamargot, & V. Berninger (Eds.). *Translation of Thought to Written Text While Composing: Advancing Theory, Knowledge, Research Methods, Tools, and Applications* (pp. 315–338). New York: Taylor & Francis/Routledge, Psychology Press.

Alamargot, D., Chesnet, D., Dansac, C., & Ros, C. (2006). Eye and pen: A new device for studying reading during writing. *Behavior Research Methods, 38*(2), 287–299.

Alamargot, D., & Morin, M.-F. (2015). Does handwriting on a tablet screen affect students' graphomotor execution? A comparison between Grades Two and Nine. *Human Movement Science, 44*, 32–41.

Alamargot, D., Morin, M.-F., Pontart, V., Maffre, L., Flouret, L., & Simard-Dupuis, E. (2014). Les enfants dyslexiques ont-ils des difficultés graphomotrices? *Approche Neuropsychologique des Acquisitions de l'Enfant, 128*, 59–67.

Amundson, S. (1995). *Evaluation Tool of Children's Handwriting.* Homer, AK: OT Kids.

Bairstow, P. J., & Laszlo, J. I. (1981). Kinaesthetic sensitivity to passive movements and its relationship to motor development and motor control. *Developmental Medicine & Child Neurology, 23*, 606–616.

Blöte, A. W., & Hamstra-Bletz, L. (1991). A longitudinal study on the structure of handwriting. *Perceptual and Motor Skills, 72*(3), 983–994.

Chan, A. H. S., & Lee, P. S. K. (2005). Effects of different task factors on speed and preferences in Chinese handwriting. *Ergonomics, 48*(1), 38–54.

Charles, M., Soppelsa, R., & Albaret, J. (2004). *Echelle d'évaluation rapide de l'écriture chez l'enfant BHK.* Paris: EAP.

Chartrel, E., & Vinter, A. (2004). L'écriture: Une activité longue et complexe à acquérir. *Approche Neuropsychologique des Apprentissages chez l'Enfant, 78*, 174–180.

Chartrel, E., & Vinter, A. (2006). Rôle des informations visuelles dans la production de lettres cursives chez l'enfant et l'adulte. *L'Année Psychologique, 106*(1), 43–63.

Chartrel, E., & Vinter, A. (2008). The impact of spatio-temporal constraints on cursive letter handwriting in children. *Learning and Instruction, 18*(6), 537–547.

Chesnet, D., & Alamargot, D. (2005). Analyse en temps réel des activités oculaires et grapho-motrices du scripteur: Intérêt du dispositif "Eye and Pen". *L'Année Psychologique, 105*(3), 477–520.

Chicoine, A.-J., Lassonde, M., & Proteau, L. (1992). Developmental aspects of sensorimotor integration. *Developmental Neuropsychology, 8*, 381–394.

Danna, J., & Velay, J.-L. (2015). Basic and supplementary sensory feedback in handwriting. *Frontiers in Psychology, 6*(169), 1–11.

Feder, K. P., Majnemer, A., Bourbonnais, D., Blaynet, M., & Morin, I. (2007). Handwriting performance on the ETCH-M of students in a Grade One regular education program. *Physical & Occupational Therapy in Pediatrics, 27*(2), 43–62.

Gerth, S., Dolk, T., Klassert, A., Fliesser, M., Fischer, M. H., Nottbusch, G., & Festman, J. (2016). Adapting to the surface: A comparison of handwriting measures when writing on a tablet computer and on paper. *Human Movement Science, 48*, 62–73.

Gerth, S., Klassert, A., Dolk, T., Fliesser, M., Fischer, M. H., Nottbusch, G., & Festman, J. (2016). Is handwriting performance affected by the writing surface? Comparing preschoolers', second graders', and adults' writing performance on a tablet vs. paper. *Frontiers in Psychology, 7*, 1308.

Girard, N., Simonnet, D., & Anquetil, E. (2017). IntuiScript a new digital notebook for learning writing in elementary schools: 1st observations. In: Paper presented at the 18th International Graphonomics Society Conference (IGS2017), Gaeta, Italy. Abstract retrieved from < https://hal.inria.fr/hal-01548200/document > .

Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology, 18*(9), 694–698.

Graham, S., Berninger, V. W., Abbott, R. D., Abbott, S. P., & Whitaker, D. (1997). Role of mechanics in composing of elementary school students: A new methodological

approach. *Journal of Educational Psychology, 89*(1), 170–182.
Graham, S., Berninger, V., Weintraub, N., & Schafer, W. (1998). Development of handwriting speed and legibility in Grades 1–9. *Journal of Educational Research, 92*(1), 42–52.
Graham, S., Struck, M., Santoro, J., & Berninger, V. W. (2006). Dimensions of good and poor handwriting legibility in first and second graders: Motor programs, visual-spatial arrangement, and letter formation parameter setting. *Developmental Neuropsychology, 29*(1), 43–60.
Hepp-Reymond, M.-C., Chakarov, V., Schulte-Mönting, J., Huethe, F., & Kristeva, R. (2009). Role of proprioception and vision in handwriting. *Brain Research Bulletin, 79*(6), 365–370.
Hulstijn, W., & Van Galen, G. P. (1983). Programming in handwriting: Reaction time and movement time as a function of sequence length. *Acta Psychologica, 54*, 23–49.
Jolly, C., Palluel-Germain, R., & Gentaz, E. (2013). Evaluation of a tactile training for handwriting acquisition in French kindergarten children: A pilot study. In H. Schwitzer, & D. Foulke (Eds.). *Kindergartens: Teaching Methods, Expectations and Current Challenges* (pp. 161–176). Hauppauge, NY: Nova Science Publishers.
Laszlo, J. I., & Bairstow, P. J. (1984). Handwriting: Difficulties and possible solutions. *School Psychology International, 5*(4), 207–213.
Mangen, A., & Balsvik, L. (2016). Pen or keyboard in beginning writing instruction? Some perspectives from embodied cognition. *Trends in Neuroscience and Education, 5*(3), 99–106.
Marquardt, C., Gentz, W., & Mai, N. (1996). On the role of vision in skilled handwriting. In M. L. Simner, C. G. Leedham, & A. J. W. M. Thomassen (Eds.). *Handwriting and Drawing Research: Basic and Applied Issues* (pp. 87–98). Amsterdam: IOS Press.
Marquardt, C., Gentz, W., & Mai, N. (1999). Visual control of automated handwriting movements. *Experimental Brain Research, 128*(1–2), 224–228.
Meulenbroek, R. G. J., & Van Galen, G. P. (1988). The acquisition of skilled handwriting: Discontinuous trends in kinematic variables. In A. M. Colley, & J. R. Beech (Eds.). *Cognition and Action in Skilled Behaviour* (pp. 273–281). Amsterdam: Elsevier.
Mojet, J. W. (1991). Characteristics of the developing handwriting skill in elementary education. In J. Wann, A. M. Wing, & N. Søvik (Eds.). *Development of Graphic Skills* (pp. 53–75). London: Academic Press.
Morin, M.-F., Lavoie, N., & Montesinos, I. (2012). The effects of manuscript, cursive, or manuscript/cursive styles on writing development in Grade 2. *Language and Literacy, 14*(1), 110–124.
Overvelde, A., & Hulstijn, W. (2011). Handwriting development in grade 2 and grade 3 primary school children with normal, at risk, or dysgraphic characteristics. *Research in Developmental Disabilities, 32*(2), 540–548.
Palmis, S., Danna, J., Velay, J.-L., & Longcamp, M. (2017). Motor control of handwriting in the developing brain: A review. *Cognitive Neuropsychology, 34*(3–4), 187–204.
Patchan, M. M., & Puranik, C. S. (2016). Using tablet computers to teach preschool children to write letters: Exploring the impact of extrinsic and intrinsic feedback. *Computers & Education, 102*, 128–137.
Pontart, V., Bidet-Ildei, C., Lambert, E., Morisset, P., Flouret, L., & Alamargot, D. (2013). Influence of handwriting skills during spelling during primary and lower secondary grades. *Frontiers in Psychology, 4*(19), 1–9.
Portier, S. J., Van Galen, G. P., & Meulenbroek, R. G. J. (1990). Practice and the dynamics of handwriting performance: Evidence for a shift of motor programming load. *Journal of Motor Behavior, 22,* 474–492.
Rueckriegel, S. M., Blankenburg, F., Burghardt, R., Ehrlich, S., Henze, G., Mergl, R., & Hernáiz Driever, P. (2008). Influence of age and movement complexity on kinematic hand movement parameters in childhood and adolescence. *International Journal of Developmental Neuroscience, 26*(7), 655–663.
Smyth, M. M., & Silvers, G. (1987). Functions of vision in the control of handwriting. *Acta Psychologica, 65*(1), 47–64.
Tamada, T. (1995). Effects of delayed visual feedback on handwriting. *Japanese Psychological Research, 37*(2), 103–109.
Teasdale, N., Forget, R., Bard, C., Paillard, J., Fleury, M., & Lamarre, Y. (1993). The role of proprioceptive information for the production of isometric forces and for handwriting tasks. *Acta Psychologica, 82*(1–3), 179–191.
Teulings, H. L., Mullins, P. A., & Stelmach, G. E. (1986). The elementary units of programming in handwriting. In H. S. R. Kao, G. P. Van Galen, & R. Hoosain (Eds.). *Graphonomics: Contemporary Research in Handwriting* (pp. 21–32). Amsterdam: Elsevier Science.
Tucha, O., Tucha, L., & Lange, K. W. (2008). Graphonomics, automaticity and handwriting assessment. *Literacy, 42*(3), 145–155.
Van Doorn, R. R. A., & Keuss, P. J. G. (1992). The role of vision in the temporal and spatial control of handwriting. *Acta Psychologica, 81*(3), 26–286.
Van Galen, G. P., Smyth, M. M., Meulenbroek, R. G. L., & Hylkema, H. (1989). The role of short-term memory and the motor buffer in handwriting under visual and non-visual guidance. In R. Plamondon, C. Y. Suen, & M. L. Simmer (Eds.). *Computer Recognition and Human Production of Handwriting* (pp. 253–271). Singapore: World Scientific.
Vinter, A., & Chartrel, E. (2010). Effects of different types of learning on handwriting movements in young children. *Learning and Instruction, 20*(6), 476–486.
Vinter, A., & Zesiger, P. (2007). L'écriture chez l'enfant: Apprentissage, troubles et évaluation. In S. Ionescu, & A. Blanchet (Eds.). *Psychologie du développement et de l'éducation* (pp. 327–351). Paris: PUF.
Von Hofsten, C., & Rösblad, B. (1988). The integration of sensory information in the development of precise manual pointing. *Neuropsychologia, 28*, 805–821.
Wann, J., & Nimmo-Smith, I. (1991). The control of pen pressure in handwriting: A subtle point. *Human Movement Science, 10*(2–3), 223–246.
Wollscheid, S., Sjaastad, J., & Tømte, C. (2016). The impact of digital devices vs. Pen(cil) and paper on primary school students' writing skills – A research review. *Computers & Education, 95*, 19–35.
Zesiger, P., Deonna, T., & Mayor, C. (2000). L'acquisition de l'écriture. *Enfance, 3*, 295–304.