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Perception of the cursive handwriting movement
in writers and pre-writers

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Abstract

27 The objective of this study was to confirm the existence of knowledge relating to the
28 cursive writing movement for French pupils in 3rd year of kindergarten, 2nd grade and 5th grade
29 of elementary school. 141 pupils were asked to watch a visual presentation of cursive
30 handwriting to determine whether they were able to detect violations of two rules of
31 handwriting: continuity and sequentiality of the cursive handwriting movement. Our results
32 showed progressive development of the understanding of characteristics of the cursive
33 handwriting movement, with different developmental trajectories of knowledge for the different
34 rules. The ability to detect continuity of the cursive writing movement developed earlier than
35 the ability to detect sequentiality. Correct decisions were not always accompanied by correct
36 justifications, which developed more slowly than detection of rule violations.

37 **Keywords:** cursive handwriting, perception, continuity, sequentiality, children.

38

39 Written verbal production is a complex activity involving a number of processes.
40 Perceptual and motor processes, generally categorized as “low level”, do not operate
41 independently of the higher-level processes, which are orthographical, lexical, syntactic, and
42 compositional (Berninger, Vaughan, Abbott, Begay, Coleman, Curtin, et al., 2002; Bourdin,
43 Cogis, & Foulin, 2010; Christensen, 2005; Medwell & Wray, 2008). The level of handwriting
44 mastery among 6- to 9-year-olds seems to affect spelling ability (Pontart et al., 2013). The same
45 has been observed in relation to compositional quality (Olive, Favart, Beauvais, & Beauvais,
46 2009). The facilitating role of motor representations associated with writing movements has
47 also been highlighted in some studies on the development of reading skills (Bara, Gentaz, Colé
48 & Sprenger-Charolles, 2004; Bartolomeo, Bachoud-Lévi, Chokron, & Degos, 2002; Velay, &
49 Longcamp, 2013).

50 New communication and information technologies are increasingly used by teachers
51 and students for writing (Matthewman & Triggs, 2004; Sutherland et al., 2004). However, in
52 France, teachers continue to use cursive writing in their classroom (Bara, Morin, Alamargot, &
53 Bosse, 2015; Bara, Morin, Montésinot-Gelet, & Lavoie, 2011). Traditionally in France, cursive
54 writing is learnt during the first year of formal education (first grade of primary school).
55 Previously, during the two last years of kindergarten, pupils discover upper-case letters and
56 learn to master the movements required to write. Usually, by the end of kindergarten, they begin
57 to produce cursive letters. While continuity and fluency of movement are characteristic of all
58 biological movements, formal writing is differentiated by its strict sequentiality which
59 determines the strokes order (Goodnow & Levine, 1973; Parkinson, Dyson, & Khurana, 2010).

60 **Writing as a Sequence of Ordered Movements**

61 Graphic production is characterized by a specific stroke order, also called the “grammar
62 of action” (Goodnow & Levine, 1973). This strict sequentiality can be observed just as well
63 during exercises involving the copying of geometric shapes (Goodnow & Levine, 1973; Vinter
64 & Marot, 2007) as during the writing of ideograms (Flores d’Arcais, 1994), Latin characters
65 (Parkinson et al., 2010; Simner, 1981; Viviani & Stucchi, 1992), or Roman characters (Velay
66 & Longcamp, 2013). While some rules are common to all types of graphic production, such as
67 (a) start on the left and (b) start from the top, others are specific to certain writing systems and
68 are introduced to facilitate the fluidity of movement, such as (c) produce loops and circles in an
69 anticlockwise direction in cursive writing and (d) for right-handed people, produce horizontal
70 strokes from left to right (Goodnow & Levine, 1973).

71 These spatio-temporal regularities are acquired with the formal learning of handwriting
72 (Wong & Kao, 1991). In France, the sequentiality of stroke order in cursive handwriting seems
73 to develop gradually in children, primarily during the course of 1st grade (Vinter & Chartrel,
74 2010). However, the grammar of action for cursive writing is not necessarily stabilized by the
75 end of that year, and it has been shown in a French study that one third of 1st grade pupils still
76 experience difficulties in following the stroke direction imposed by their teacher (Bonneton-
77 Botté & De La Haye, 2009).

78 It is worth noting that the sequentiality of stroke order is thought to be a facilitating
79 element in the memory encoding process. Parkinson et al. (2010) showed that when they
80 presented letters stroke by stroke and varied the order of the strokes, adult observers used the
81 memory of the order of the strokes that formed the letter to recognize it more quickly in a
82 reading situation. The authors concluded that the participants had used the memory of their
83 motor program for letters to manage this task, but they also highlighted the fact that participants

84 had been completely unaware that they were using this strategy. When questioned on how they
85 had gone about responding to the task, they tended to make spontaneous writing motions in the
86 air to describe the motor sequence associated with producing a letter, rather than offering any
87 verbal explanation.

88 **Continuity of the Writing Movement**

89 The writing movement, like the drawing movement, is also characterized by a principle
90 of continuity, which limits the number of pauses produced during the gesture (Goodnow &
91 Levine, 1973). For the expert writer, for example, harmonious writing produced in a continuous
92 movement involves the implementation of optimal strategies, which will have required, most
93 notably, to chunk together a number of small units (the strokes) in memory to form higher-level
94 units (letters, syllables, or words). This chunking process is thought to allow motor programs
95 corresponding to high-level units to be triggered, which then facilitates the automation process
96 (Lambert & Espéret, 1997; Kandel, Héroult, Grosjacques, Lambert, & Fayol, 2009). It is
97 assumed that this cognitive economy results in a reduction in the number of intra-word pauses.

98 Paz-Villagràn, Danna and Velay (2014) proposed to distinguish two kinds of pauses:
99 stops and lifts. Lifts are characterized by the fact that the pen is no longer in contact with the
100 paper. Stops instead refer to any discontinuity in graphomotor activity without the pencil having
101 been lifted off the page and excluding any unavoidable inter-letter penlift. Such stops have been
102 traditionally interpreted in psychology as an indicator of a cognitive activity (Foulin, 1995).
103 Research has only recently started studying stops, so as to understand their meaning and their
104 developmental course for children with and without learning disabilities (Brun-Hénin, Velay,
105 Beecham & Cariou, 2013; Maldarelli, Kahrs, Hunt & Lockman, 2015; Paz-Villagràn, Danna &
106 Velay, 2014; Prunty, Barnett, Wilmut & Plumb, 2014). If stops are too numerous or too long,
107 they may prove to be the consequence of a low level of visual attention (Maldarelli et al., 2015)

108 or of motor difficulties (Paz-Villagràn et al., 2014; Prunty et al., 2014). Researchers observed
109 a significant reduction of the mean stop duration between the ages of 8 and 14 (Zesiger, 1992,
110 Prunty et al., 2014; Alamargot, Plane, Lambert, & Chesnet, 2010). Moreover, Zesiger (1992)
111 noted that between the ages of 8 and 12 as well as at adult age, 80% to 90% of stops are located
112 at the juncture between two strokes and that intra-stroke stops are rare. This progressive ability
113 to control movement on the basis of a motor program is thought to enable children to produce
114 a relatively rapid, continuous writing movement by the end of elementary school.

115 **The Influence of Visual Perception in the Learning Process**

116 It is frequently assumed that spatio-temporal organization of the traces and size of motor
117 programs changes under the influence of the formal learning process of writing (Bo, et al., 2014;
118 Zesiger, 1992). Nevertheless, some research has shown that it is also possible to bring about a
119 change in the grammar of action through repeated observation or implicit learning in both adults
120 (Babcock & Freyd, 1988; Vinter & Perruchet, 1999; Weeks & Anderson, 2000) and children
121 (Vinter & Perruchet, 2000, 2002). In fact, Parkinson and colleagues. (2010) have highlighted
122 that interactions between perception and action are bidirectional. Perception of a motor
123 sequence triggers coding of the action, and the motor sequence then affects perception by
124 creating an expectation of the visual result produced by this same action. This embodied
125 cognition would explain the observer's ability to predict the course of dynamic visual events
126 (Kandel, Orliaguet, & Viviani, 2000). A study, carried out by Chartrel and Vinter (2010),
127 showed that presenting the dynamic trace of the letter during a teaching session had a beneficial
128 effect on the handwriting performance of children aged five and a half. The authors suggested
129 that the participants processed information about the trajectory of the strokes during observation
130 and then transferred it during motor production.

131 This interpretation remains hypothetical, and more research would be necessary to
132 determine what the children perceived and understood about a proficient cursive writing
133 movement. While researchers have been able to define the writing movement in terms of its
134 continuity and sequentiality, is it also possible for children to perceive and use these
135 characteristics? Do they perceive all or only some of features of the movement, and at what
136 stage in the learning and development process do they acquire these skills?

137 **Objectives**

138 The present research explores the ability of pre-writers (3rd year of kindergarten) and
139 writers (2nd grade and 5th grade) to detect the presence of irregularities in a visually presented
140 cursive handwriting movement. Irregularities were presented in the form of unusual stops
141 (intra-stroke) and violations of the grammar of action rules (changes in the order or direction
142 of intra-letter strokes) in a cursive writing movement produced by an adult expert writer. Taking
143 into account the reciprocal influence of action and perception and the place of cursive writing
144 in the French educational system, four hypotheses were formulated: (Hypothesis 1) because
145 continuity is characteristic of human movement (like drawing for instance; Goodnow & Levine,
146 1973) and because intra-stroke stops are unusual in proficient adult cursive handwriting (Paz-
147 Villàgran et al., 2014), children as young as 3rd year of kindergarten pupils should be able to
148 detect an irregularity (the presence of unusual intra-stroke stops) in a cursive writing movement
149 even though they have not yet mastered this motor skill; (Hypothesis 2) because, unlike
150 continuity, the ordered sequence of strokes is specific to handwriting (Goodnow & Levine,
151 1973; Parkinson et al., 2010; Velay & longcamp, 2013; Wong & Kao, 1991) and is acquired at
152 a later stage, generally during 1st and 2nd grade, it is reasonable to assume that pre-writers will
153 not detect an irregularity of the ordered sequence of the strokes that compose the letters as
154 frequently as intra-strokes stops; (Hypothesis 3) taking into account the combined influence of

155 motor mastery (Louis Dam et al., 2000; Bildet-Ildei et al., 2006) and learning process (Chartrel
156 & Vinter, 2010) that occurs during perception of handwriting movement, we anticipate that the
157 ability to detect irregularities will increase with school level; (Hypothesis 4) even for children
158 who demonstrate the ability to detect irregularities, previous observations (Kandel et al., 2000;
159 Chartel & Vinter, 2010; Parkinson et al., 2010) lead us to believe that they will not necessarily
160 manage to explain or verbalize their decision; in other words, we expect to observe the ability
161 to detect irregularities without the ability to verbalize, regardless of school level.

162 **Method**

163 **Participants**

164 A total of 141 pupils participated in the study, which took place in their school. There
165 were 45 3rd year of kindergarten pupils (24 boys and 21 girls, mean age 5 years and 5 months),
166 52 2nd grade pupils (28 boys and 24 girls, mean age 7 years and 6 months), and 44 5th grade
167 pupils (18 boys and 26 girls, mean age 10 years and 5 months). The 141 students came from
168 three different schools. The sample included only right-handed children, as assessed by
169 Auzias's test of handedness (Auzias, 1975), and none of them presented any particular disorder.
170 The kindergarten pupils didn't begin the formal cursive handwriting at the time of the
171 experiment. Even if they had already learnt to trace upper-case letters, we considered them pre-
172 writers regarding their cursive handwriting experience. Teachers and parents were informed of
173 the nature of the task proposed to the children and all gave their informed consent for the
174 research.

175 **Materials**

176 Each pupil was asked to observe 15 (plus one example) short video sequences of a white
177 gloved hand writing a pseudo-word on a whiteboard with a blue marker pen. Colors of the glove

178 and of the marker pen were chosen to make the trace more salient. The pseudo-words were
179 written by a 1st grade teacher, who had undergone training in writing pseudo-words while
180 making changes to her usual writing characteristics. Each child viewed the sequences on a
181 computer screen positioned at a distance of 30 cm. The size of the hand was true to life to keep
182 the situation as realistic as possible.

183 We chose to present pseudo-words as opposed to real words in order to help participants
184 focus their attention on the writing movement rather than the meaning of the word. Because we
185 anticipated that participants who were able to read would immediately try to read the pseudo-
186 words, they were created with an appropriate level of difficulty to offset this potential
187 interference. The pseudo-words were thus developed by decomposing frequently used French
188 words (using the *Manulex* database; see Lété, Sprenger-Charolles, & Colé, 2004) in such a way
189 that the number of syllables was equivalent to real French words. All pseudo-words were
190 composed of six or seven letters. Taking into account the inherent fatigability of children of the
191 age groups involved in the study, we chose to limit the number of pseudo-words to 15. The
192 choice of 15 different pseudo-words was made to avoid a learning effect during the task and to
193 prevent pupils from memorizing and comparing items.

194 Five pseudo-words were presented without irregularities and used as control words; five
195 had a stop artificially inserted into two letters (intra-stroke stop); and in the remaining five, two
196 letters were traced without respecting the usual order and direction of the strokes. To
197 summarize, the three categories were:

- 198 - Five pseudo-words containing no modifications (Control condition).
- 199 - Five pseudo-words containing continuity irregularities: certain letters were written with
200 intra-stroke stops (Stop condition; see online resource 1).

201 - Five pseudo-words containing sequentiality irregularities: certain letters were written
202 without respecting the basic grammar of action rules (Direction condition; see online
203 resource 2).

204 On average, the pseudo-words were written in 8.2 seconds, which represents a relatively slow
205 writing speed.

206 In the Stop condition, time taken to write the pseudo-words was standardized so that the
207 additional breaks has no effect on the overall length of time taken to write the word; this control
208 was made in an effort to focus the experiment on the spatio-temporal organization of the stops.
209 The basic average length of time taken to write the item was recorded when the teacher was
210 first asked to write the pseudo-words (no time constraint was imposed upon her). The teacher
211 then produced models with the two additional stops, and the sequence was speeded up slightly
212 to offset the writing time involved in the added stops.

213 The two inserted stops differed from lifts (Mojet, 1991, Paz-Villagràn et al., 2014)
214 because of unbroken contact between the marker pen and the medium, and because of their
215 intra-letter location. As we were interested in children's knowledge about adult proficient
216 cursive handwriting, the average stopping time was 0.5 seconds which is longer than the
217 average duration stop (0,23 ms) for proficient adults (Paz-Villagràn et al., 2014). The teacher
218 made stops in the middle of a stroke (in the vertical stroke of a *d* or *p* or in the loop of an *l* or *e*
219 for instance), which is rare in adult writing. We made sure that the added stops were noticeable
220 by pre-testing the items on 10 adults, all of whom were able to notice and locate them.

221 As for the Direction condition, we chose to modify the basic rules of writing for frequent
222 letters (*e/p/t/l/p/d/o/c*). Loops were produced in a clockwise rather than counter-clockwise
223 direction. Downstrokes were produced from bottom to top rather than from top to bottom, and
224 the horizontal stroke of the *t* was produced from right to left. The order of the strokes within a

225 letter composed of several strokes was modified, and the loops of the *d* and *p* were produced
226 after the downstroke. Each of the pseudo-words comprised both a looped letter (*e* or *l*) and a
227 letter composed of strokes. As in the stop condition, two letters had an abnormal direction in
228 each pseudo-word.

229 **Procedure**

230 The tests took place individually in a calm environment within the children's school.
231 The instructions were as follows:

232 You're going to see a hand writing some words. These words don't exist, they don't
233 mean anything. Sometimes, the hand will write the word really well, and sometimes it
234 will write the word in a strange way. Every time I show you a word, I want you to tell
235 me whether the writing is strange or not.

236 Presentation of the words was randomized to avoid any interference from the order of
237 testing. The researcher recorded 1 or 0, corresponding to success and failure respectively, for
238 each response depending on whether or not the child responded correctly. Each participant
239 therefore obtained a score from zero to five for each of the three conditions. This score was
240 considered the detection score.

241 Items identified as "strange" were immediately revisited with the child to obtain an
242 explanation for their decision; they were asked "Why do you think it's strange?" Children were
243 not asked to explain their decision when they considered the writing to be normal. Explanations
244 for identifying an item as "strange" in the Control condition were not analyzed in detail, both
245 because the focus of the present study was on the detection of violations, and because all
246 explanations provided by children in this condition were unrelated to the continuity and
247 sequentiality of movements. Explanations in the Stop and Direction conditions were split into

248 two categories: correct explanation, and incorrect or no explanation. For the Stop condition, a
249 good explanation would demonstrate that the child was aware that there had been a rupture in
250 the continuity of the writing movement (e.g. "it seems like it pauses", "because it stops",
251 "normally it should carry on without stopping"). For the Direction condition, a good explanation
252 would bring out the idea of order or direction (e.g. "it didn't do the line in the right direction",
253 "you don't write *e* like that"). When, on occasion, the child used more gestures than words to
254 explain (e.g. "it did that [the child shows the direction of the trace with their finger], when you
255 should do that"), we deemed this to be admissible, because it was clear the child was aware of
256 the nature of the irregularity in the presented trace. The "incorrect or no explanation" category
257 represented either an absence of explanation or an inadequate explanation (e.g. "I think it does
258 it wrong there", "I don't do an *s* like that" with the child referring to a letter with no irregularity).
259 Categorization of the responses was carried out by two independent judges, and no
260 disagreements were observed.

261 **Data Analysis**

262 The data were screened for outliers using Cook's distance for all analyses. We first
263 performed an analysis of variance to test the effect of items, so as to make sure that the five
264 pseudo-words in each of the three conditions were comparable. A mixed-design analysis of
265 variance was then applied to detection scores, so as to determine whether they varied as a
266 function of school year and/or experimental condition. Post-hoc tests were performed using
267 Tukey's honestly significant difference (HSD) set at the .05 level, which is appropriately
268 conservative in the case of multiple comparisons.

269 Next, we analyzed the proportion of correct responses correctly explained for each
270 participant, computed as the ratio of the number of correct explanations over the number of
271 correct detections. To ensure that the results were independent of the child's actual detection

272 performance, this analysis was restricted to children producing at least one correct response per
273 condition (Kindergarten: $n = 38$; 2nd grade: $n = 43$; 5th grade: $n = 40$). One-sample t tests were
274 conducted to test whether the proportion of correct explanations was significantly below one,
275 indicating that correct decisions were not necessarily accompanied by correct explanations. A
276 mixed-design analysis of variance was used to determine whether the proportion of correct
277 explanations differed as a function of school level and experimental condition.

278 **Results**

279 **Children's Abilities to Detect Irregularities**

280 Are pre-writer children able to detect irregularities in a cursive writing movement? How
281 does this ability develop between 3rd year of kindergarten, 2nd grade, and 5th grade? Are the
282 different writing movement features treated equally?

283 The results of an analysis of variance checking for a possible item effect revealed no
284 significant difference between the items in either the Control conditions $F(4, 560) = 0.65, p =$
285 $.621$; the Stop condition $F(4, 560) = 1.47, p = .202$; the Direction condition $F(4, 560) = 1.47, p$
286 $= .209$), thus confirming that all pseudo words were of comparable difficulty.

287 Table 1 presents descriptive statistics for detection scores as a function of school level
288 and experimental condition. Descriptively, detection scores demonstrated a clear increase from
289 2nd grade onwards. It is also worth noting that average scores did not reach the maximum, even
290 in 5th grade.

291 [Insert Table 1 approximately here]

292 A mixed-design analysis of variance was performed with school level and experimental
293 conditions (Control, Stop, and Direction) as the independent variables and detection score as
294 the dependent variable. The main effect of school level was significant, $F(2, 138) = 36.93$,

295 $p < .001$, $\eta^2_p = .35$, indicating that the number of successful responses significantly increased
296 as a function of school level. The main effect of condition was also significant,
297 $F(2, 276) = 8.86$, $p < .001$, $\eta^2_p = .06$; post hoc tests indicated that the Control condition showed
298 significantly more successful responses than the other two conditions. Lastly, the two-way
299 interaction between school level and experimental condition was significant, $F(4, 276) = 2.98$,
300 $p = .020$, $\eta^2_p = .04$, indicating that perception of the features of handwriting across the three
301 conditions differed as a function of grade. This interaction is represented in Figure 1.

302 [Insert Figure 1 approximately here]

303 Post hoc tests revealed that scores in the Control condition and in the Direction condition
304 increased throughout the three school levels (all $ps \leq .01$); scores in the Stop condition
305 remained stable between kindergarten and 2nd grade ($p = .962$) but increased significantly
306 between 2nd grade and 5th grade ($p < .001$). Kindergarten pupils performed at the same level for
307 the Control and Stop conditions ($p = .967$) and significantly lower in the Direction condition.
308 2nd grade pupils performed significantly higher in the Control condition than in the Stop and
309 Direction conditions, which did not differ. Lastly, 5th grade pupils performed at comparable
310 levels in all conditions (all p

311 **Children's Ability to Justify their Answers**

312 When the pupils detect an irregularity, are they able to explain what seems strange to
313 them? Is this ability to explain constant for each of the movement features?

314 Table 2 presents descriptive statistics for the proportion of correct explanations as a
315 function of school level and condition, for children who made at least one correct decision in a
316 condition. Descriptively, the rate of correct explanations rose steadily as a function of school
317 level; it only exceeded 50% during 5th grade and never reached 100%. Correct explanations

318 from the youngest participants were rare, especially in the Direction condition. One-sample t-
319 tests confirmed that correct detections were not necessarily accompanied by correct
320 explanations, for any of the age groups and experimental conditions: the average proportion of
321 correct explanations remained significantly below one in all cases (all $ps \leq .001$).

322 [Insert Table 2 approximately here]

323 The results of the mixed-design analysis of variance are displayed in Figure 2. The
324 analysis revealed a main effect of grade, $F(2, 118) = 49.98, p < .001, \eta^2_p = .46$, with the
325 proportion of correct justifications steadily increasing with school level. The main effect of
326 condition was also significant, $F(1, 118) = 14.58, p < .001, \eta^2_p = .11$, indicating that the Stop
327 condition elicited more correct justifications than the Direction condition. Lastly, the two-way
328 interaction between grade and condition was not significant, $F(2, 118) = 0.07, p = .936$,
329 $\eta^2_p = .00$. Post hoc tests confirmed that the proportion of correct explanations significantly
330 increased for each successive grade in both conditions

331 Discussion

332 The objective of this research was to examine, in the context of French education, the
333 ability of pre-writers and writers to perceive the characteristics of a cursive writing movement.
334 The study focused on assessing whether, for the cursive handwriting, children at both the pre-
335 writing and writing stages were able to detect that a writing movement conformed to general
336 (continuity of movement) and specific (order and direction of strokes) motor production rules
337 (Goodnow & Levine, 1973). The formulation of our first two hypotheses led us to expect that
338 knowledge about the continuity and the sequentiality of movement would not be the same for
339 pupils in 3rd year of kindergarten as for those in 5th grade. At what point would participants be
340 able to detect an abnormal discontinuity? Given that continuity of movement is a general feature
341 of motor production (Goodnow & Levine, 1973) and that intra-stroke stops are unusual in

342 proficient adult handwriting (Paz-Villagràn et al., 2014), we had assumed that our participants,
343 even those who had not yet mastered the cursive handwriting skill, would be aware of the
344 continuity of movement feature.

345 By comparing the three conditions we observed that kindergarten pupils perform better
346 when confronted with typical writing or when the writing movement presents an abnormal
347 discontinuity. The idea of cognitive representations that are isomorphic to the real world
348 (Perruchet, 2008) leads us to suppose that, in France, a country attached to cursive writing
349 (Bara, Morin, Alamargot, & Bosse, 2015; Bara, Morin, Montésinot-Gelet, & Lavoie, 2011),
350 children regularly presented with the movement would gradually and implicitly be able to work
351 out that the writing movement was a continuous movement. Because continuity is, in particular,
352 a rule that characterize drawing movements (Goodnow & Levine, 1973), they probably,
353 therefore, have a representation of what the continuity of a motor sequence must be even before
354 cursive writing becomes part of their motor repertoire.

355 This knowledge, which seems difficult to verbalize, has already been shown by
356 Orliaguet, Kandel, and Boë (1997) to exist in adults. While the adults in their study were able
357 to predict the identity of the letter following the *l* from information on the movement of the
358 trace, they reported that they nevertheless felt their responses were random. Similarly, many
359 kindergarten pupils showed an awareness of the continuity of movement characteristic (80% of
360 kindergartners identified more than half the control sequences as correct; only 42% wrongly
361 identified more than half the sequences with intra-stroke stops as correct), but the implicit status
362 of the information may have prevented them from being able to explain a violation of this
363 characteristic. We nevertheless note that, in kindergarten, one third of correct detections of
364 discontinuity were associated with a correct explanation, showing that the awareness of
365 continuity and of discontinuity can, from this age onwards, be subject to conscious processing.

366 Although our study does not explain them, the existence of these individual differences is
367 interesting from a developmental standpoint. Some children may either have had a richer visual
368 experience of the cursive writing action in their personal environment, or their learning of
369 cursive writing may have already begun in their family environment. A possible perspective
370 would be to conduct this research in countries that culturally favor script writing in order to
371 investigate the sensitivity of children to the continuity or discontinuity of a cursive writing.
372 Furthermore, it would be relevant to examine knowledge of writing movements in pupils who
373 mainly use information and communication technologies.

374 For Vinter and Chartrel (2010), presenting a dynamic trace of the letter during a teaching
375 session had a beneficial effect on the handwriting performances of children aged five and a half.
376 In their conclusion, they suggested that the participants processed the traced trajectory
377 information during observation and then transferred it during motor production. Our results
378 show that, out of a teaching session, dynamic information relative to the continuity of a
379 proficient cursive handwriting movement can be extracted by 3rd year of kindergarten pupils
380 and consciously processed, at least in part.

381 In contrast to continuity, the ordered sequence of strokes is very specific to the cursive
382 handwriting movement (Goodnow & Levine, 1973; Parkinson et al., 2010; Velay & Longcamp,
383 2013; Wong & Kao, 1991) and is acquired later in development, usually during 1st and 2nd grade
384 (Bonneton-Botté, De La Haye, Marec-Breton, & Bara, 2012). We therefore assumed that
385 perception of the sequentiality of the writing movement would emerge later than that of the
386 continuity of movement. A comparison of the results from the three conditions and an analysis
387 of the explanations given by the children in the Stop and Direction conditions support this
388 assumption.

389 The distinctive status of this feature became clear when we analyzed the kindergarten
 390 pupils' results. When presented with a violation of the order and direction of the strokes, they
 391 reported most of the time that nothing was unusual in the movement observed. The average
 392 detection score of 2 indicates that they responded on average three times out of five that the
 393 movement was normal, which corresponded almost exactly with their response rate in the
 394 Control condition. Contrary to the Stop condition, the few children who did detect direction
 395 irregularities were rarely able to produce a correct explanation for their answer. The ability to
 396 detect direction irregularities rose considerably in 2nd grade, catching up with the performance
 397 observed for the Stop condition. Detection was equivalent for both conditions in 5th grade.
 398 However, our qualitative analysis of the pupils' explanations showed that these two conditions
 399 were not, in fact, equivalent because verbalization was still easier in the Stop condition. We can
 400 assume, therefore, that the children's perception and knowledge of the order and direction of
 401 strokes characterizing cursive writing was more dependent on what they had been taught at
 402 school.

403 While this assumption that explicit learning plays a role is probably true, it is not the
 404 only possible explanation. Vinter and Chartrel's (2008) study showed that 2nd grade also
 405 corresponds to the developmental period during which retroactive control becomes established.
 406 During this period, visual feedback is instrumental to the control of all motor production. The
 407 analysis of visual information relating to movement and its resulting trace could form the
 408 developmental foundations of representations that are useful for controlling subsequent motor
 409 production, labelled by Schmidt (1975) as "recognition schemata". The statistically significant
 410 increase from kindergarten to 2nd grade in the detection of irregularities in the stroke order
 411 could, therefore, be explained both by the school's explicit teaching of this new grammar of

412 action and by this new possibility of comparing the sensory consequences of the movement
413 with the recognition schemata of mastered traces.

414 To sum up so far, we have shown that the two features of continuity and sequentiality
415 do not follow the same developmental trajectories. Continuity seems to be essentially part of a
416 general domain of knowledge, namely movement, whereas sequentiality belongs to a specific
417 domain of knowledge, namely writing (Karmiloff-Smith, 1992). The process of constructing
418 knowledge about the two features is, therefore, assumed to be dissimilar. Knowledge of
419 continuity appears early on in development and is globally more frequent than knowledge of
420 sequentiality. A complementary study of 1st grade pupils would allow us to better identify the
421 relation between the sequentiality knowledge and the beginning of the formal learning process.

422 Our third hypothesis assumed that an increase in school level (corresponding to
423 development of motor control with age and to explicit learning at school) would be associated
424 with an increase in ability to detect the characteristics of the cursive writing movement. We
425 assumed that school level would reflect the implicit and explicit learning about motor function
426 and perception acquired by children throughout the school curriculum. In particular, our
427 objective was to compare the response profiles of kindergarten pupils, who had not yet received
428 any formal cursive writing instruction, 2nd grade pupils, whose cursive writing learning was still
429 in progress, and 5th grade pupils, who were deemed to have completed the school curriculum
430 as far as cursive writing was concerned. In accordance with this prediction, we showed that, for
431 each of the features studied, an increase in school level was accompanied by an increase in
432 movement irregularity detection and in the children's ability to give a good explanation for their
433 response. However, it is impossible to assign this change in the response profiles to one factor
434 in particular, because there were many potential factors involved. These increases in school
435 level correspond to many perceptive, cognitive and motor developmental advances: i) the

436 ability to use vision prospectively to plan and guide reading and handwriting actions (Maldarelli
437 et al., 2015; Norton & Wolf, 2012); ii) the creation of multimodal representations of letters
438 followed by syllables and then morphemes (Kandel & Perret, 2015); iii) the growing motor
439 repertoire from which the subject can visually explore a movement (Calvo-Merino et al., 2006;
440 Velay & Longcamp, 2013).

441 In our final hypothesis, we supposed that, for French pupils, the ability to detect
442 irregularities in a handwriting cursive movement would not necessarily be explainable or
443 verbalizable at the three school levels examined. The existence of implicit knowledge of motor
444 rules, which is difficult to verbalize, has already been shown in adults for different motor
445 domains (Berry & Broadbent, 1984; Kandel et al., 2000; Orliaguet, Kandel, & Boë, 1997;
446 Parkinson et al., 2010; Reber, 1967). Our results conformed with this hypothesis: on average,
447 the proportion of correct explanations was reliably below one, and it was necessary to wait for
448 the 5th grade to record a majority of correct explanations for either experimental condition. For
449 all school levels, it always seemed more difficult to give a good justification when the
450 irregularity concerns the order of the strokes. As we mentioned above, the learning process and
451 the progressive building of motor rules could explain those differences. Nevertheless,
452 understanding why certain subjects, whatever the age, are able to perceive and verbalize motor
453 rules when others are not, remains a challenge for future research.

454 **Conclusion**

455 Perceptive, motor and cognitive activities all contribute to advances in the development
456 of handwriting skills. In this research, we have tried to determine to what extent the dynamical
457 characteristics of cursive handwriting could constitute a conscious and verbalizable domain of
458 knowledge. Prior to mastering cursive writing, some kindergarten pupils were able to perceive
459 irregularities relative to stops in a cursive handwriting movement; but, they were rarely able to

460 be explain their answer. With age, throughout learning and increases in visuo-motor expertise,
461 pupils were able to develop an explicit knowledge about the stops that characterize the
462 production of an expert writer. At the same time, we observed that knowledge about the
463 appropriate sequentiality of cursive handwriting is set up later and remains more difficult to put
464 into words for all three school levels.

465 We would like to stress the fact that these results offer research perspectives in response
466 to the concerns of those who develop reading and writing teaching protocols. Because children
467 are able to perceive and to handle consciously certain characteristics of a dynamic model of
468 writing, it is relevant to show them dynamic models of cursive handwriting during the learning
469 process. This is now made much easier by means of new technologies such as tablet computers
470 (Alamargot & Morin, 2015; Jolly, Palluel-Germain, & Gentaz., 2013). Nevertheless, more
471 studies are needed to make sure that a teaching method including explicit learning of the
472 dynamical characteristics of cursive handwriting could be beneficial, in particular, to the
473 youngest children, who do not necessarily have the neuromotor maturity to begin motor
474 training.

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639 Table 1. *Descriptive statistics for detection scores as a function of grade.*

	Kindergarten	2nd grade	5th grade
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
Control	3.20 (1.14)	4.29 (1.05)	4.23 (1.01)
Stop	2.87 (1.59)	3.19 (1.85)	4.20 (1.30)
Direction	2.20 (1.31)	3.40 (1.47)	4.09 (1.38)

640 *Note.* The table represents averages (standard deviations). Average detection scores ranged
641 from 0 to 5.

642

643 Table 2. *Descriptive statistics for the proportion of correct justifications as a function of grade*
644 *for the Stop and Direction conditions.*

	Kindergarten	2nd grade	5th grade
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
Stop	0.23 (0.35)	0.48 (0.46)	0.86 (0.27)
Direction	0.07 (0.24)	0.35 (0.41)	0.73 (0.34)

645 *Note.* The table represents averages (standard deviations). This analysis was restricted to
646 children who produced at least one correct response per condition (Kindergarten: $n = 38$; 2nd
647 grade: $n = 43$; 5th grade: $n = 40$).

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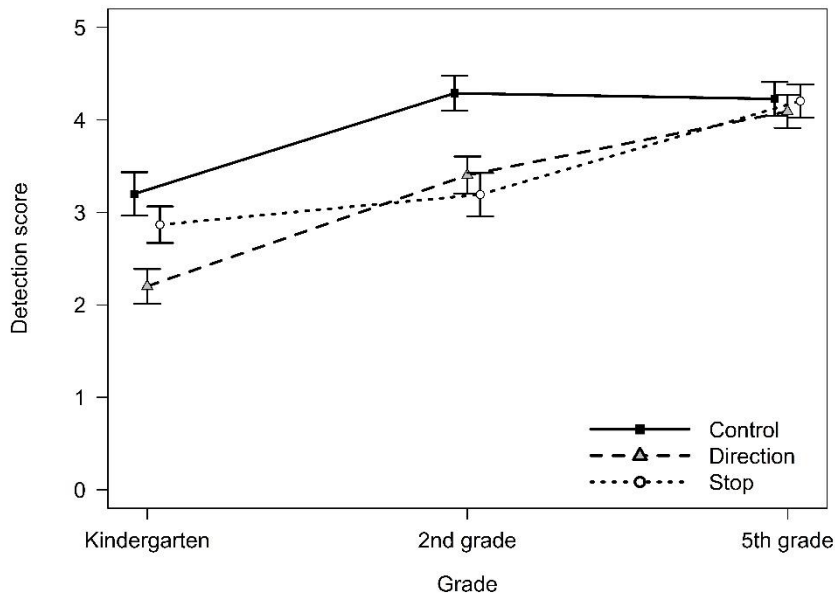
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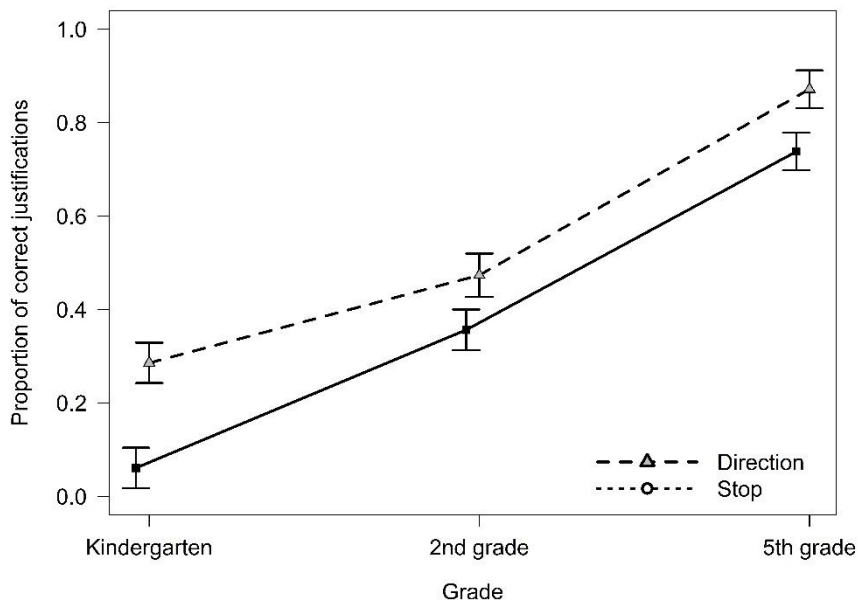
658 *Figure 1.* Average detection scores as a function of grade and experimental condition. Error
659 bars represent within-subjects standard errors of the mean (Morey, 2008).

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666 *Figure 2.* Average proportion of correct explanations for detected irregularities as a function of
667 grade for the Stop and Direction conditions. Error bars represent within-subjects standard errors
668 of the mean (Morey, 2008).