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## Orthographic learning of novel words in adults: Effects of exposure and visual attention on eye movements

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### ABSTRACT

Eye movement monitoring was used to explore the time course of orthographic learning in adult skilled readers while they read novel words presented in isolation one, three or five times. Off-line measures of spelling-to-dictation and orthographic decision were used to measure orthographic memorization. Further, the participants' visual attention span was estimated. Results showed better memorization of new words' orthography with additional exposures. An exposure-by-exposure in-depth analysis of eye movements revealed an early sharper decrease for the number of fixations and most measures of processing time. Participants with a higher visual attention span showed better performance in orthographic decision and processing times. The overall findings suggest that orthographic learning occurs from the first exposure and that top-down effects from the newly acquired orthographic knowledge would facilitate processing from the second exposure. Further, time needed for bottom-up information extraction appears to be modulated by visual attention span.

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### KEYWORDS

Orthographic Learning; Visual Attention; Eye Movement; Orthographic Decision; Incidental Learning

## 1. Introduction

Memorization of the orthographic form of thousands of words is critical to become a fluent reader and a good speller (Castles et al., 2018; Treiman, 2017). Orthographic learning is mainly incidental, occurring with exposure to printed words via reading experience. Despite the key role of orthographic learning in both reading – for the visual recognition of printed words – and writing – for word-specific spelling, we still have little insight into how learning affects new printed word processing and what are the cognitive mechanisms at play. In this paper, we explore the orthographic learning of new words using eye-tracking, which allows studying the learning process as reading unfolds, thus in an online manner. Furthermore, while most previous studies have emphasized the impact of phonological decoding on orthographic learning (e.g., Bowey and Muller, 2005; Castles and Nation, 2006; Share, 1999), we here examine whether the visual attention capacity, as measured through tasks of visual attention span (VA span), has a role on the orthographic learning of novel words.

15 A diversity of methods has been used to explore orthographic learning. The most  
16 popular is the self-teaching paradigm proposed by David Share in his seminal experi-  
17 ments (Share, 1999, 2004). In this paradigm, participants are administered a learning  
18 phase followed by a test phase. During the learning phase, they are asked to read aloud  
19 meaningful stories in which target pseudo-words – introduced as names for fictitious  
20 places, animals, fruits, etc. – are embedded in short texts. Each story introduces a  
21 single target pseudo-word that can be repeated a few times per text. Orthographic  
22 learning is assessed during the following test phase that is proposed immediately or  
23 some days/months after text reading. Three tasks were initially designed to gauge the  
24 acquisition of the target pseudo-word orthographic form: an orthographic choice task,  
25 that required identifying the target pseudo-word alongside a homophonic foil (e.g.,  
26 YAIT-YATE), a naming task, in which the targets (e.g., YAIT) and their foils were  
27 randomly displayed and naming reaction times recorded, and a spelling task.

28 Results of Share’s seminal studies showed that orthographic learning occurred  
29 after only a few encounters with the novel word. Evidence of orthographic learning  
30 has been reported after a single encounter (Nation et al., 2007; Share, 2004) and  
31 one to four encounters appear to be sufficient for relatively durable memorization of  
32 the target specific orthography (Bowey & Muller, 2005; Nation et al., 2007; Share,  
33 1999, 2004; Tucker et al., 2016). Further, studies revealed that orthographic learning  
34 could occur out of context. Effective learning was not only reported for novel words  
35 embedded in meaningful texts but also in scrambled passages (Cunningham, 2006)  
36 or when presented in isolation (Bosse et al., 2015; Landi et al., 2006; Nation et al.,  
37 2007; Share, 1999; Wang et al., 2011). Most previous studies explored incidental  
38 orthographic learning in children (from the first grade to later grades). Written word  
39 learning was also explored in adults but mainly using intensive repetitions with  
40 explicit instruction and/or artificial languages (Taylor et al., 2011).

41  
42 One issue with the orthographic learning paradigm is that it does not straightfor-  
43 wardly provide evidence that learning was effective following exposition to the novel  
44 words. The validity and reliability of the tasks used to assess orthographic learning  
45 have been debated (Castles & Nation, 2008). Among the tasks initially used by Share  
46 (1995, 1999), the orthographic choice task is one of the most popular, but simultaneous  
47 presentation of alternative orthographies in this paradigm may induce strategy-based  
48 processing without tapping the word recognition process. Moreover, performance tends  
49 to be high and thus not sensitive enough to orthographic learning. In contrast, perfor-  
50 mance on the spelling task was typically reported as drastically low in children (Bosse  
51 et al., 2015; Cunningham, 2006) and the task not sensitive enough to reflect ortho-  
52 graphic learning (Castles & Nation, 2008). Some alternative solutions to these more  
53 standard tasks have been proposed, like word recognition tasks allowing to measure  
54 word length effects (Martens & De Jong, 2008) or tasks of matching between a new  
55 word and its definition (Joseph et al., 2014), but these measures were also found to  
56 lack sensitivity.

57 In the present study, an orthographic decision task inspired from Wang et al. (2011)  
58 was administered as a potential new alternative. In this task, targets and homophonic  
59 foils were displayed one at a time and participants had to respond either YES if the  
60 written form corresponded to the spelling of the learned novel word, or NO otherwise.  
61 Presentation of a single written form at a time in this orthographic decision task  
62 prevents the strategy-based responses reported in the orthographic choice task and  
63 more naturally taps the word recognition process. Moreover, response accuracy and  
64 reaction times were both recorded to increase task sensitivity. Orthographic learning

65 was further evaluated through a spelling task where participants were asked to spell  
66 the target novel words. The use of the spelling task with children was debated, but  
67 higher performance and better sensitivity was here expected for adults. This task  
68 which requires fully specified orthographic information about the target is particularly  
69 relevant to assess target-specific orthographic memorization. While the memorization  
70 tasks provide off-line measures of orthographic learning, eye movements appear as  
71 providing insights on the online learning process.

72  
73 Most research on eye movements in reading have focused on real word processing  
74 in text reading (Rayner, 1998, 2009). Some studies have investigated the effect of a  
75 single encounter with pseudo-words on eye movements (Chaffin et al., 2001; Lowell  
76 & Morris, 2014; Wochna & Juhasz, 2013). While there was no pseudo-word effect on  
77 fixation location (Lowell & Morris, 2014), more refixations were reported for pseudo-  
78 word processing and extra processing-time was needed for pseudo-words as compared  
79 to familiar words. These findings are consistent with reports of word frequency effect  
80 on eye movements (Rau et al., 2015; Schilling et al., 1998; Williams & Morris, 2004),  
81 suggesting that the pseudo-words were processed as low-frequency words would be.

82 Only a few studies have investigated how eye movement measures are affected by  
83 repeated exposure to the same novel word in conditions of incidental learning. Joseph  
84 et al. (2014) explored eye movements while English-speaking adult participants read  
85 pseudo-words embedded in sentences. The stimuli were bisyllabic 6-letter pseudo-words  
86 that were presented in short stories (i.e., 15 exposures to each of the 16 pseudo-word)  
87 during the 5-day sessions of the learning phase. Eye movement tracking revealed an  
88 effect of repeated exposure on pseudo-word processing time, shorter first fixation dura-  
89 tion and shorter single fixation duration being reported over repeated sessions. Pellicer-  
90 Sanchez (2016) also reported significant repeated exposure effects on the number of  
91 fixations and total reading time during the incidental learning of 6-letter pseudo-words  
92 presented for reading in meaningful contexts. Eye movement variations with repeated  
93 exposures were also incidentally observed by Gerbier et al. (2015, 2018) but using a  
94 reading-while-listening paradigm in 6th grade French pupils. In this paradigm, par-  
95 ticipants processed pseudo-words embedded in meaningful texts while listening to the  
96 spoken version of the text through headphones. Twelve 2-syllable pseudo-words were  
97 presented four times each in different stories. Online eye movement monitoring re-  
98 vealed a decrease of the first fixation duration and a tendency to shift the first fixation  
99 location to the right across repetitions.

100 Overall, eye movement monitoring while reading novel words appears as particu-  
101 larly useful for the real-time study of orthographic learning (Nation & Castles, 2017).  
102 Most previous studies focused on the effect of the learning context on eye movements,  
103 focusing on the order-of-acquisition (Joseph et al., 2014), contextual diversity, spacing  
104 and retrieval practice (Pagan & Nation, 2019) or the diversity of semantic contexts  
105 (Joseph & Nation, 2018). Only a few studies manipulated the number of exposures  
106 and studied eye movement changes throughout exposures (Gerbier et al., 2015, 2018;  
107 Joseph & Nation, 2018; Joseph et al., 2014). However, these studies provided no  
108 in-depth analysis of eye-movement changes from exposure to exposure (see however  
109 Pellicer-Sanchez, 2016). In the present study, we monitored eye movements while  
110 participants read novel words that were presented in isolation and which they were  
111 exposed to from one to five times. This paradigm allows an exposure-by-exposure  
112 tracking of eye-movement changes during novel word orthographic learning, thus  
113 providing direct insight on the online learning process. Furthermore, the time course  
114 of eye movements on target novel words was compared with that of real words to

115 disentangle repetition effects from orthography learning effects. We reasoned that eye  
116 movements may be sensitive to repetition effects, the fact that the same printed items  
117 were presented several times during the reading phase. Similar repetition effects were  
118 expected on both the novel words and the familiar words but stronger orthographic  
119 learning effects were expected for the novel words. As a result, any across-exposure eye  
120 movement effect specific to the novel-words (a Word Type by Exposure interaction)  
121 would be interpreted as evidence in support of orthographic learning.

122  
123 The self-teaching hypothesis (Share, 1995, 1999) asserts that phonological decoding  
124 is the central mechanism by which orthographic knowledge is acquired. When exposed  
125 to a novel word, readers have to decode the word, using their general letter-sound  
126 mapping knowledge to generate the novel word’s spoken form. The theory posits that  
127 every time the novel word is successfully decoded, the reader has the opportunity to  
128 memorize its orthographic form. Some computational models that have implemented  
129 the self-teaching mechanism (Pritchard et al., 2018; Ziegler et al., 2014) illustrate the  
130 critical role of phonological decoding in the development of orthographic knowledge.  
131 This central role is supported by experimental findings showing that accurate decoding  
132 is a powerful predictor of incidental orthographic learning (Ricketts et al., 2011) and  
133 that orthographic learning is lower in conditions of concurrent articulation (de Jong et  
134 al., 2009; Kyte & Johnson, 2009; Share, 1999). However, despite the well-documented  
135 role of phonological decoding in orthographic knowledge acquisition, there is also ev-  
136 idence that decoding does not guarantee orthographic learning when successful and  
137 does not systematically prevent orthography acquisition when unsuccessful (Castles &  
138 Nation, 2006, 2008; Nation et al., 2007; Tucker et al., 2016).

139 Beyond decoding skills, other factors like prior orthographic knowledge and print ex-  
140 posure do predict the quality of orthography learning (Cunningham, 2006; Stanovich &  
141 West, 1989; Wang et al., 2014), suggesting the involvement of additional orthographic  
142 (Cunningham et al., 2001) or visual-orthographic (Share, 2008) processing skills during  
143 self-teaching. The impact of visual-orthographic processing on orthographic learning  
144 was directly addressed by Bosse et al. (2015) in a self-teaching paradigm. In their  
145 study, either the whole letter-string of printed bi-syllable pseudo-words was simulta-  
146 neously displayed, or the first and second syllables were presented successively one at  
147 a time during the learning phase. In both conditions, children were asked to utter the  
148 spoken form of the entire pseudo-word after presentation. For the pseudo-words that  
149 were accurately decoded, results revealed better orthographic learning when the entire  
150 pseudo-word letter-string was simultaneously available for visual processing during the  
151 learning phase. Beyond decoding skills, this suggests that orthographic learning fur-  
152 ther depends on the learner’s capacity to attend simultaneously to the whole sequence  
153 of letters of the novel word while reading.

154 A number of previous studies have also provided indirect evidence that orthographic  
155 acquisition relates to the capacity for multielement simultaneous processing, that is,  
156 the VA span (Bosse et al., 2007). Typically, VA span is estimated through tasks of  
157 multi-letter or multi-digit oral report but the VA span is not specific to verbal tasks  
158 and alphanumeric material. It can be very similarly estimated using non-verbal tasks  
159 and non-verbal stimuli, like symbols or pseudo-letters (Chan & Yeung, 2020; Lobier  
160 et al., 2012). Performance on VA span tasks reflects the amount of visual attention  
161 capacity available for processing (Dubois et al., 2010; Lobier et al., 2013), which  
162 relates to the dorsal attention network (Lobier et al., 2014; Lobier et al., 2012; Reilhac  
163 et al., 2013; Valdois, Lassus-Sangosse, et al., 2019; Valdois et al., 2014). Individuals  
164 with higher VA span show more efficient word recognition skills, thus faster reading

165 (Antzaka et al., 2017; Bosse & Valdois, 2009; Lobier et al., 2013; Valdois, Roulin, et al.,  
166 2019), more accurate irregular word reading (Bosse & Valdois, 2009) and smaller  
167 length effects (van den Boer et al., 2013); for computational modeling, see Ginestet  
168 et al. (2019). Exploration of their eye movements during text reading revealed lesser  
169 fixations and larger saccades, suggesting that more letters were simultaneously pro-  
170 cessed per fixation (Prado et al., 2007). Overall, these findings suggest that individuals  
171 with higher visual attention capacity may more efficiently identify a higher number  
172 of letters simultaneously while reading, which would boost letter-string processing  
173 and facilitate orthographic learning. The present study for the first time explored  
174 the potential impact of VA span on the incidental orthographic learning of novel words.  
175

176 Our main purpose was to provide new insights on the process of orthographic learn-  
177 ing. Eye movement monitoring was used during the learning phase to track ortho-  
178 graphic learning online through the analysis of cross-exposure effects on eye move-  
179 ments. The paradigm we used – repeated exposition to novel words presented without  
180 context – offered the opportunity to track the exposure-by-exposure evolution of eye  
181 movements for an in-depth analysis of the online learning process. Furthermore, real  
182 words were presented mixed to the target pseudo-words during the reading phase  
183 and in similar conditions of eye movement recording for a baseline measure to which  
184 pseudo-word processing was compared. Any between-exposure variation of eye move-  
185 ments for words was interpreted as mainly reflecting repetition effects. By comparison,  
186 any differential effect for the target pseudo-words would be interpreted as evidence of  
187 orthographic learning. The off-line tasks were administered after the learning phase to  
188 ensure that any variation of eye movements as a function of the number of exposures  
189 might be interpreted as reflecting on-line orthographic learning.

190 As previously reported in self-teaching paradigms, we expected better performance  
191 on the off-line measures of orthographic learning (i.e., spelling-to-dictation and or-  
192 thographic decision tasks) with increased exposure to the target pseudo-words. With  
193 respect to the online measures of eye-movement, better learning would translate into  
194 fewer fixations and shorter processing time across exposures during reading. In line  
195 with behavioral evidence that orthographic learning occurs from the first exposure  
196 (Share, 2004), significant eye movement changes were expected to occur very early,  
197 mainly between the first and second exposures. The words of mid-to-high frequency  
198 used as baseline were expected to have stable orthographic memories, thus limiting on-  
199 line memorization effects. Accordingly, interactions between the number of exposures  
200 and the item type (words or pseudo-words) are expected on number of fixations and  
201 processing time, as a marker of novel word orthographic acquisition clearly different  
202 from a simple item repetition effect.

203 Another goal of the present study was to explore the potential influence of multi-  
204 element simultaneous processing skills on target pseudo-word processing and ortho-  
205 graphic learning, through the administration of off-line tasks of VA span. We predicted  
206 eye movements and orthographic learning to vary depending on the participants' VA  
207 span skills. Participants with higher VA span would be more prone to identify a higher  
208 number of letters simultaneously while reading, which would affect both eye movement  
209 measures and orthographic learning. We predicted that participants with a higher VA  
210 span would show better orthographic learning, thus higher performance in spelling  
211 and in orthographic decision. They might further exhibit faster learning over time  
212 than lower VA span participants, which might result in faster decrease in number of  
213 fixations and processing time across exposures.

## 214 2. Method

### 215 2.1. Participants

216 Forty-six undergraduate students ( $n_{Female} = 36$ ) participated in the experiment. All  
217 participants were native French-speakers with normal or corrected-to-normal vision  
218 and no known learning or reading disorders. None of them showed an abnormally low  
219 performance in a spelling-to-dictation control task of 30 irregular real words (mean  
220 = 60.1 %; SD = 12.9; range: 40–90). They received a 20 € compensation for their  
221 participation. Informed written consent was obtained from each participant and the  
222 study was approved by the ethics committee for research activities involving humans  
223 (CERNI number: 2018-Avis-02-06-01) of the Grenoble-Alpes University. It was thus  
224 performed in accordance with the ethical standards of the declaration of Helsinki.

### 225 2.2. Protocol

226 Each participant was first engaged in an incidental learning phase followed by a test  
227 phase. During the learning phase, they were asked to read aloud real control words and  
228 target pseudo-words that were mixed and displayed 1, 3 or 5 times each on the screen  
229 while their eye movements were recorded. To ensure incidental learning, no explicit  
230 instruction was given to participants to take notice of novel words’ orthography: the  
231 participants were instructed to read aloud the stimuli and they were not informed  
232 that the purpose of the study was to test their orthographic knowledge of the target  
233 pseudo-words. Two tasks of spelling-to-dictation and orthographic decision were used  
234 in the test phase to estimate their pseudo-word orthographic learning. The two tasks  
235 were systematically administered in the same order, spelling-to-dictation first. Global  
236 and partial letter-report tasks were further administered to measure the participants’  
237 VA span.

### 238 2.3. The learning phase

#### 239 2.3.1. Material

240 **2.3.1.1. Pseudo-words.** A list of pseudo-words was designed to be used for implicit  
241 learning. Thirty legal bi-syllabic 8-letter pseudo-words were generated by reference to  
242 the French lexical database LEXIQUE (New et al., 2001). They were built up from  
243 existing trigrams (mean  $f_{trigram} = 1,655$ ; SD  $f_{trigram} = 1,176$ ; range: 327–4,144) to  
244 have no orthographic neighbors (i.e., none differed from a real word by a single letter).  
245 None was homophone to a real word. Each pseudo-word contained at least two ambigu-  
246 ous graphemes, that is, graphemes corresponding to phonemes that could be written  
247 in at least two different ways. For example, the target pseudo-word *GOUCIONT* cor-  
248 responding to the phonological form / gusjõ / would be written *GOUSSION* when  
249 following the most frequent phoneme-to-grapheme mappings in French. Moreover, at  
250 least another pseudo-word of the list included the same phoneme but correspond-  
251 ing to another ambiguous grapheme that was not the most often associated to this  
252 phoneme in French. For example, the phoneme /õ /, spelled *ONT* in *GOUCIONT*, was  
253 spelled *OND* in *TRIMPOND*. Furthermore, to prevent any systematic visual explo-  
254 ration strategy during the learning phase, the ambiguous graphemes’ positions were  
255 varied between items, so that they could be located at the beginning, middle left,  
256 middle right or at the end of the pseudo-word letter-string. A critical point in the

257 current study is to ensure that novel words accurate spellings cannot be derived from  
258 their phonological form. Therefore, a control experiment was carried out to estimate  
259 the probability of accurate by-default spellings. The lists of the target novel words and  
260 their homophones were dictated to a group of 30 students, none of them participating  
261 to the orthographic learning experiment. On average, 3.1 % of the collected spellings  
262 were identical to those of the target pseudo-words (3.4 % for the homophones). There-  
263 fore, significantly higher evidence of correct spellings than the 3.1 % spontaneously  
264 collected would support orthographic learning.

265 To investigate the effect of the number of exposures (1, 3 or 5), three different subsets  
266 of pseudo-words (noted A, B and C; see Test Lists in A.1) were created. The three lists  
267 were matched in orthographic features – position and number of ambiguous graphemes  
268 and mean trigram frequency (respectively, 1627.4, 1668.6, 1668.5). They were further  
269 matched in “orthographic difficulty”, controlling for the number of possible spellings  
270 that complied with the pseudo-word pronunciation.

271 **2.3.1.2. Control words.** The thirty control words were 8-letter long with no ortho-  
272 graphic neighbors. All were of medium frequency (per million, mean  $f_W = 35.57$ ; SD  
273  $f_W = 18.86$ ). As for pseudo-words, the word list was divided into three sublists (noted  
274 A, B and C; see Test Lists in A.2) balanced with respect to their mean frequencies  
275 (respectively, 34.44, 36.03, 35.93).

### 276 2.3.2. Apparatus

277 All stimuli were displayed on a computer screen (DELL, Round Rock, Texas, United  
278 States) using a  $1680 \times 1050$  px resolution and a 60 Hz refresh rate. Stimuli were  
279 presented on a black background in white lowercase Courier New font (size 32 px)  
280 and experiments were designed with the open-source experiment builder Opensesame  
281 (Mathôt et al., 2012; v.3.1.2).

282 During the reading phase, the participants’ eye movements were monitored using  
283 a RED250 eye tracker (SMI® company, Teltow, Germany) at a viewing distance of  
284 67 cm. The system was interfaced with a laptop (Latitude E6530, DELL, Round Rock,  
285 Texas, United States) and gaze position recording was performed by the iViewX soft-  
286 ware (SMI® company, Teltow, Germany). Each character covered a horizontal visual  
287 angle of  $0.47^\circ$ , and each 8-letter stimulus covered a  $3.76^\circ$  visual angle. To minimize  
288 head movements, participants kept their forehead pressed on a frontal support.

### 289 2.3.3. Procedure

290 A first listening phase without visual display was administered to each participant.  
291 The pronunciation of the target pseudo-words was heard through headphones. The  
292 “canonical” pronunciation provided through headphones followed the most frequent  
293 grapheme-to-phoneme correspondences. Participants were instructed to listen carefully  
294 to the pronunciation of the new words (pseudo-words) as they would have to read them  
295 aloud in the second phase. The rationale for providing “canonical” pronunciations was  
296 to avoid having different participants refer to different pronunciations.

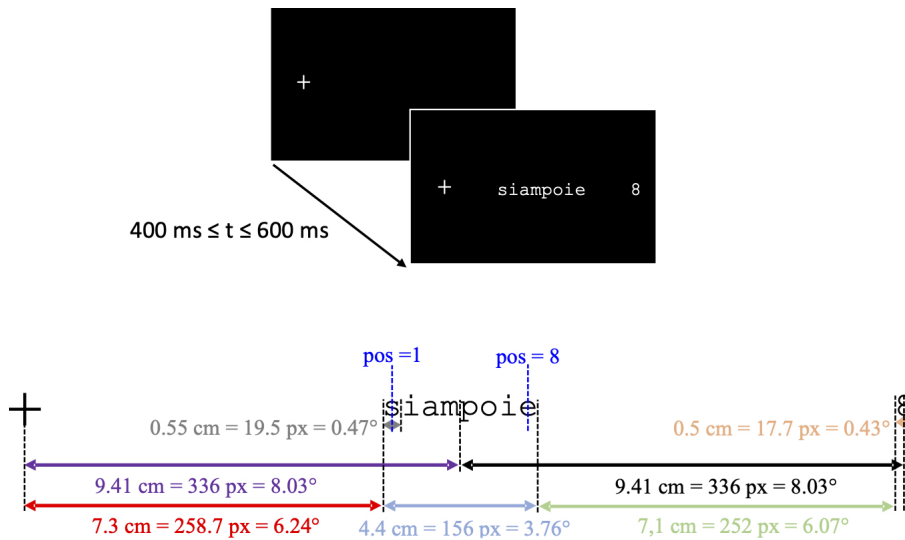
297 After the initial listening phase, the eye-tracker was calibrated, using a five-point  
298 calibration procedure. Then, the learning phase started. Each trial began with the  
299 presentation of a fixation cross. Participants were instructed to keep their eyes on the  
300 cross; doing so long enough (randomized time ranged from 400 ms to 600 ms) would  
301 trigger the display of the stimulus on the screen.



302 A stimulus was composed of a control word or a pseudo-word and a digit from 1 to  
 303 9 (see Figure 1). The two items (word or pseudo-word and digit) were simultaneously  
 304 presented on the horizontal line, the digit always right of the written item. To avoid  
 305 any phenomenon of spatial habituation or anticipation, the position of the fixation  
 306 cross was varied randomly from 204 px to 804 px horizontally left to the center of the  
 307 screen. The distance between the fixation cross and the letter-string and between the  
 308 letter-string and the digit was fixed, and set to 9.41 cm (8.03° at a viewing distance  
 309 of 67 cm).

310 Participants were asked to read aloud as naturally as possible the written word  
 311 or pseudo-word, then the digit. This induced a processing sequence (fixation cross  
 312 then item then digit) ensuring a left-to-right scanning on the item while avoiding  
 313 atypical fixations during first pass on the novel word due to interference with end of  
 314 processing. Then, they pressed the space bar of the keyboard to trigger the next trial.  
 315 No feedback was provided during the task. Drift correction and re-calibration of the  
 316 eye-tracker could be performed at any time by the experimenter if necessary, with drift  
 317 correction systematically performed every 10 trials.

318 Ten items, pseudo-words and real words, were displayed once each; ten items were  
 319 displayed three times each and ten five times; for a total of 180 trials. The trials were  
 320 presented with a different, random order for each participant. The number of exposures  
 321 was counterbalanced across subjects, so that, for example, Participant 1 would read  
 322 the pseudo-words and control words from Lists A, B and C respectively once, three  
 323 times and five times, whereas Participant 2 would read Lists A, B and C respectively  
 324 five times, once and three times, etc. The reading task was preceded by 4 practice  
 325 trials (see Practice Lists in A.1 and A.2) during which feedback was provided. The  
 326 participants' naming responses were scored as correct or incorrect.



**Figure 1.** Experimental design. Top: illustration of the time course of a trial during the learning phase. Bottom: distances (in cm, pixels and degrees) between items and reference frame for counting letter positions (illustrated by pos=1 for the first and pos=8 for the last letter).

327 **2.4. Test phase**

328 **2.4.1. Unexpected pseudo-word spelling-to-dictation test**

329 Immediately after the learning phase, participants performed a spelling-to-dictation  
330 task to measure how well they had memorized the experimental pseudo-words. The oral  
331 pronunciation of each pseudo-word was successively presented through headphones,  
332 once each, without repetition, and in a random, different order for each participant.  
333 Participants had to type each pseudo-word immediately after its pronunciation on the  
334 computer keyboard. They were instructed that the pseudo-words were those which  
335 they had been previously exposed to and were explicitly asked to spell them as they  
336 were spelled during the learning phase. Overall, 30 pseudo-words (see Test Lists in  
337 A.1) were written by each participant. No time limit was imposed and participants  
338 triggered the next trial at their convenience. No feedback was provided to the partic-  
339 ipants. Two scores were computed from the participants' spellings. A whole pseudo-  
340 word spelling score corresponding to the number of spellings strictly identical to the  
341 target orthography and a by-grapheme spelling score corresponding to the number of  
342 target graphemes that were accurately spelled. The latter measure was expected to be  
343 potentially more sensitive to orthographic learning than the former.

344 **2.4.2. Orthographic decision test**

345 Target pseudo-words' learning was further assessed through an orthographic decision  
346 task. In this task, each target pseudo-word was paired with a pseudo-homophone.

347 **2.4.2.1. Stimuli.** Thirty pseudo-homophones (see Test List in A.3) were gener-  
348 ated following the same criteria as for the pseudo-words. The pseudo-homophones  
349 were matched to the pseudo-words in trigram frequency (mean  $f_{trigram} = 1,391$ ; SD  
350  $f_{trigram} = 1,040$ ; range: 307–3,829). The written form of each pseudo-homophone in-  
351 cluded at least one ambiguous grapheme that differed from that of the related target  
352 pseudo-word (e.g., *SAITTEAU-CEITTEAU*, *PHACRAIS-PHACRAIT*, *SIEMPOIT-*  
353 *SIAMPOIE*).

354 **2.4.2.2. Protocol.** Each item (target pseudo-word or pseudo-homophone) was suc-  
355 cessively displayed on the computer screen one at a time. The participants were asked  
356 to decide as quickly and as accurately as possible whether the displayed item was  
357 spelled as the target pseudo-word or not. Each trial began with a fixation cross dis-  
358 played at the center of the computer screen during 500 ms. The fixation cross was im-  
359 mediately replaced by a forward mask composed of eight hash marks (#####) for  
360 500 ms. The target was then displayed, centered on fixation, until the participant's  
361 response.

362 Presentation order was randomized and different for each participant. No feedback  
363 was provided to the participants. The two possible response buttons were the left  
364 button (for a "Yes" response) and the right button (for a "No" response) of a serial  
365 response (SR) box. A total of 60 targets were presented: the 30 target pseudo-words  
366 read during the learning task (see Test Lists in A.1) and the 30 pseudo-homophones  
367 (see Test List in A.3). The task was preceded by 4 practice trials (see Practice List in  
368 A.1 and A.3) during which feedback was provided. Accuracy and reaction times were  
369 recorded.

## 370 **2.5. VA span tasks**

371 The participants were administered global and partial report tasks to estimate their VA  
372 span. The tasks followed the protocol described by Antzaka et al. (2017) which we only  
373 summarize in the following. At each trial, a 6-consonant string was briefly displayed  
374 centered on the fixation point. The consonant string was built-up from 10 consonants  
375 (B, P, T, F, L, M, D, S, R, H) with no repeated letter. The consonant string was  
376 presented in black uppercase Arial font on a white background. Inter-letter spacing  
377 was increased to avoid crowding ( $0.57^\circ$  inter-consonant space). Twenty-four strings  
378 were successively presented in the global report task, 72 in the partial report task. In  
379 both tasks, trials began with a fixation dot displayed at the center of the screen during  
380 1 s, immediately followed by a blank screen during 50 ms. The 6-consonant string was  
381 then displayed for 200 ms.

382 In the global report task, participants were told to verbally report as many letters  
383 as possible immediately after string presentation, regardless of the letter position in  
384 the string. In the partial report task, a single vertical bar appeared for 50 ms ( $1.1^\circ$   
385 below one of the letter positions) at the offset of the consonant string, indicating the  
386 position of the letter to be reported. The experimenter typed the participants' response  
387 without providing any feedback. The experimenter then proceeded to the next trial by  
388 pressing the Enter key. Both tasks were preceded by 10 practice trials during which  
389 feedback was provided. The strings were displayed in a random order that differed for  
390 each participant.

391 Accuracy was recorded for the two tasks of VA span as the number of target letters  
392 accurately reported, which induces a maximum score of 144 (for 24 trials  $\times$  6 letters per  
393 trials) and 72 (one letter per trials) for the global and partial report task respectively.  
394 In order to give the same importance to each task, the total score of VA span ( $TS_{VAS}$ ,  
395 expressed as a percentage) was calculated, for each participant, using the following  
396 relation:

$$TS_{VAS} = \frac{(Global_{score} + 2 \times Partial_{score}) \times 100}{2 \times 144} \quad (1)$$

## 397 **3. Results**

398 We first consider results of the orthographic memorization tasks to evaluate the inci-  
399 dental learning of the pseudo-words' orthographic form. Next, we analyze eye move-  
400 ments during the reading phase, focusing on how they are affected by the number of  
401 exposures to target pseudo-words. Last, we explore whether and how VA span affected  
402 orthographic learning while reading.

### 403 **3.1. Statistical models**

404 The data were analyzed by means of generalized linear mixed effects models (`glmer`  
405 function; R Core Team, 2018; RStudio version 1.0.143) for all dependent variables.  
406 Participants and items were introduced as random factors. We used the Gamma fam-  
407 ily and the identity link for reaction times (RT) data (including temporal measures  
408 from eye-tracking data), the Poisson family and the identity link for the analysis of  
409 the number of fixations and the Binomial family and the logit link for binomial vari-

410 ables such as accuracy. Initially, a maximal random effects structure was specified  
411 for all models, which included all subject and item random intercepts and random  
412 slopes (Barr et al., 2013). If a model failed to converge, we followed Barr et al. (2013)  
413 suggestion removing first correlations between random factors then random interac-  
414 tions. When a model still did not converge, we dropped random slopes associated with  
415 smaller variance, until the model converged. In all models, contrasts were specified  
416 as 0.5/-0.5, 1/0/-1 or 2/1/0/-1/-2 when independent variables have, respectively, 2,  
417 3 or 5 modalities. Specific details of the models used are provided in Supplementary  
418 Material<sup>1</sup> (for a quick access, see the .html file from “Statistical\_files” folder).

419 All models related to orthographic memorization tasks included the number of ex-  
420 posures (3 modalities; 1, 3 and 5 exposures) as fixed factor. In all models related to  
421 eye-tracking data, number of exposures (5 modalities; from 1 to 5 exposures), item  
422 type and their interaction were specified as fixed factors. In order to distinguish the  
423 number of exposure effect from the trial order effect, the order of presentation of items  
424 (continuous variable from 1 to 180) was also included in these main models as covari-  
425 able, except for the analysis of the number of fixations for which the statistical model  
426 failed to converge. Finally, we explored the effect of VA span on all the online and  
427 offline measures only using pseudo-word data. Two sets of analyses were computed in  
428 which VA span was either used as a continuous variable or a discrete variable defining  
429 two groups of participants with higher or lower VA span. Results of the two groups  
430 are presented in the paper. The number of exposures, VA span group and their inter-  
431 action were specified as fixed factors. The reported effects of the VA span group on  
432 eye movements or offline measures were further found significant when using VA span  
433 as a continuous variable. However, the statistical models that used VA span as a con-  
434 tinuous variable did not converge for any of the three offline measures (pseudo-word  
435 spelling scores, orthographic decision scores and RTs) and one of the online measure  
436 (number of fixations).

437 Post-hoc comparisons were performed using Tukey contrasts in orthographic memo-  
438 rization tasks – spelling-to-dictation and orthographic decision. Based on expectations  
439 that orthographic learning would occur very early after the first exposure, analyses  
440 modeling local interactions between the first and second exposure and between the  
441 second and third exposure were computed for all the eye-tracking measures, using  
442 similar generalized linear mixed effects models than previously described, excluding  
443 the order of presentation of items as covariable.

444 The whole statistical models were performed on the data from 42 participants, due  
445 to the exclusion of four participants following clean-up of eye movement data (see  
446 subsection 3.3.1).

### 447 ***3.2. Performance in Orthographic memorization***

448 Results from both the target pseudo-word spelling-to-dictation and orthographic de-  
449 cision tasks are summarized in Table 1. Results showed a significant main effect of the  
450 number of exposures on performance in the spelling-to-dictation task either consider-  
451 ing the whole word scoring ( $\beta = 0.43$ ,  $z = 3.68$ ,  $p < .001$ ) or the by-grapheme scoring  
452 ( $\beta = 0.20$ ,  $t = 4.60$ ,  $p < .001$ ). The pseudo-words were more accurately spelled when  
453 they had been more often encountered during the reading phase. While performance  
454 on the whole pseudo-word spelling score significantly improved between the first and

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<sup>1</sup>Open access availability for Supplementary Material files: [https://osf.io/fa87h/?view\\_only=1df862ea1d0745698400c6c946eb7d26](https://osf.io/fa87h/?view_only=1df862ea1d0745698400c6c946eb7d26)

455 the fifth exposure to the same pseudo-word ( $\beta = 0.81$ ,  $z = 2.49$ ,  $p = .034$ ), a signifi-  
456 cant effect of exposure on the by-grapheme score was observed from the third exposure  
457 ( $\beta = 0.30$ ,  $z = 3.29$ ,  $p = .003$ ). None of the other contrasts was significant. We fur-  
458 ther checked whether whole pseudo-word spelling performance differed from by-default  
459 spellings at the first exposure. Comparison of participants performance after a single  
460 exposure (11.4 %) significantly differed from by-default spelling performance of people  
461 who were never exposed to the novel words (3.1 %;  $\beta = 1.92$ ,  $z = 4.67$ ,  $p < .001$ ).  
462 The overall results suggest that incidental orthographic learning was effective during  
463 the reading phase.

**Table 1.** Performance on the target pseudo-words (mean and standard deviation) as a function of the number of exposures for the spelling-to-dictation and the orthographic decision tasks.

Exp.	PW spelling-to-dictation		Orthographic decision			
	strict scoring	by-grapheme scoring	Targets PW		Homophones	
	% correct	Total Score	RTs	% correct YES response	RTs	% correct NO response
1	11.4 (9.0)	40.8 (4.2)	1231 (470)	54.6 (15.6)	1284 (492)	58.3 (17.0)
3	16.4 (15.0)	43.8 (4.4)	1114 (419)	72.8 (16.2)	1284 (500)	48.9 (17.6)
5	21.4 (16.2)	44.9 (5.0)	1007 (254)	79.6 (12.4)	1229 (395)	50.8 (16.3)

464 With respect to the orthographic decision task, trials with log-duration more than  
465 2.5 standard-deviations from the mean were excluded from analyses (1.35 % of the  
466 trials). Both the percentage of correct responses and RTs obtained in the orthographic  
467 decision task are presented in Table 1. In the absence of orthographic learning, choices  
468 in orthographic decision were expected to be merely random (around 50 %). A one-  
469 sample t-test showed that the proportion of correct choices (combining all exposure  
470 levels) was significantly above chance for the target pseudo-words ( $\beta = 18.94$ ,  $t =$   
471  $11.75$ ,  $p < .001$ ) but not for their homophones ( $\beta = 13.54$ ,  $t = 1.24$ ,  $p = .222$ ). The  
472 above-chance-level performance on the targets was found for both the three-exposure  
473 ( $\beta = 22.80$ ,  $t = 9.10$ ,  $p < .001$ ) and the five-exposure ( $\beta = 29.79$ ,  $t = 15.40$ ,  $p < .001$ )  
474 conditions.

475 Further analyses were performed on response accuracy and RTs but only for the  
476 target pseudo-words, due to random performance on the homophones. An effect of the  
477 number of exposures was expected on the two measures if orthographic learning oc-  
478 curred during the reading phase. Indeed, target pseudo-words were recognized more ac-  
479 curately ( $\beta = 0.69$ ,  $z = 6.59$ ,  $p < .001$ ) and faster ( $\beta = -86.20$ ,  $t = -6.36$ ,  $p < .001$ )  
480 across exposures. Post-hoc comparisons show that the number-of-exposures effect was  
481 significant on both response accuracy and RTs from one to three exposures (accuracy:  
482  $\beta = 1.00$ ,  $z = 4.84$ ,  $p < .001$ ; RTs:  $\beta = -141.00$ ,  $z = -171621.00$ ,  $p < .001$ ) and only  
483 on RTs from three to five exposures (accuracy:  $\beta = 0.39$ ,  $z = 1.84$ ,  $p = .157$ ; RTs:  
484  $\beta = -137.80$ ,  $z = -118569.00$ ,  $p < .001$ ). Above-chance-level performance on the  
485 target pseudo-words and more efficient pseudo-word recognition (accuracy and RTs)  
486 across exposures both support that orthographic learning did occur during the reading  
487 phase. Evidence for significant learning effects after only three exposures suggest that  
488 three or perhaps two exposures are sufficient for orthographic learning.

### 489 3.3. Analyses of eye movements during the learning phase

#### 490 3.3.1. Data cleaning

491 Although we recorded eye-tracking data for the two eyes, only data from the right eye  
492 were analyzed. Parsing raw data from the eye-tracker (i.e., event detection) was done  
493 using the BeGaze software (SMI® company, Teltow, Germany). The High-Speed al-  
494 gorithm was used, keeping default parameter values: minimum saccadic duration was  
495 22 ms, peak speed threshold of a saccade was 40°/s and minimum fixation duration  
496 was 50 ms. A custom-designed software was further used to select the relevant fix-  
497 ations for subsequent analyses. Visual inspection of the vertical coordinates of each  
498 participant led to remove those fixations located too far from the horizontal line. Using  
499 this method, we removed 1.71 % of the total number of fixations (835 fixations out  
500 of 48,865 fixations). To explore eye movements during online orthographic learning,  
501 we focused the analyses on the oculomotor events occurring during the first-pass of  
502 letter-string processing. The oculomotor events were taken into account for further  
503 analyses if occurring within an area of interest defined as follows: fixations further  
504 than 30 px (0.72°) to the left of the left boundary of the first letter, or further than  
505 30 px (0.72°) to the right of the right boundary of the last letter, were excluded from  
506 analyses.

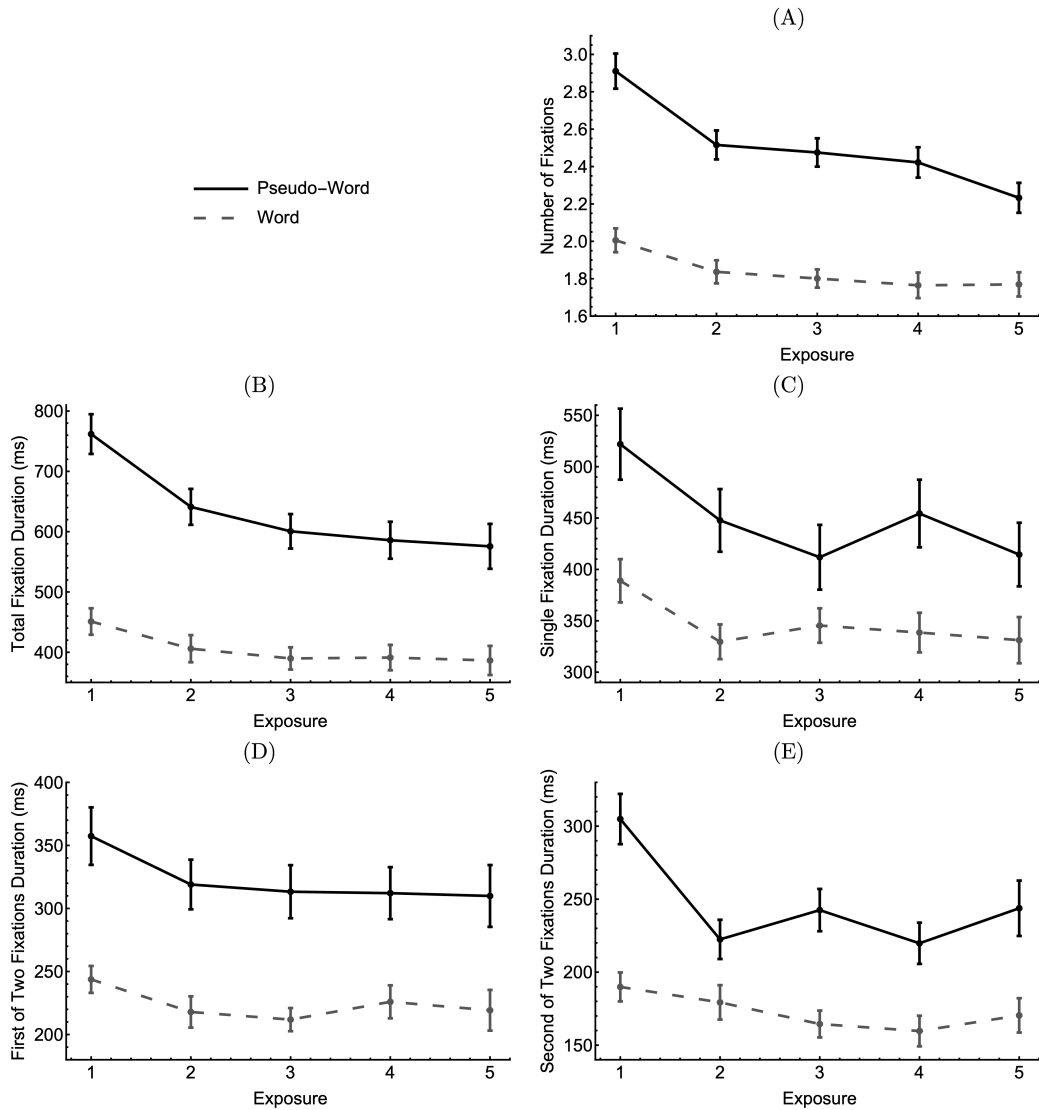
507 For all analyses, trials that showed more than one blink on the target pseudo-word  
508 were excluded. We further excluded trials with more than 8 saccades or 9 fixations  
509 that were considered as extreme outliers according to a quartile-based criterion (more  
510 saccades than  $Q_3 + 3 \times (Q_3 - Q_1)$ ). Trials with total log-duration further than 2.5  
511 standard-deviations from the mean were further excluded (range: 79–2,402 ms). Fi-  
512 nally, trials containing at least one fixation log-duration greater than 2.5 standard-  
513 deviation from the mean (i.e., more than 1,055 ms) were excluded from the analyses.  
514 The whole data from four participants were discarded due to the low percentage of  
515 trials remaining after data cleaning (< 65%). Overall, 90.66 % of the trials (6854 out  
516 of 7560 trials, see Table 2 for details) from 42 participants were kept for further anal-  
517 yses. Learning effects were first explored on the whole population before focusing on  
518 potential differential effects depending on the participants' VA span abilities.

519 Reading scores revealed that, on average, participants correctly (i.e., using the  
520 canonical pronunciation, that is to say, the pronunciation heard during the initial  
521 presentation phase) read more than 85 % of the target pseudo-words, whatever the  
522 number of exposures. Figure 2 summarizes results for the different eye movement mea-  
523 sures of interest across exposures: number of fixations, total fixation duration, single  
524 fixation duration, duration of the first-of-two fixation, duration of the second-of-two  
525 fixation. The number of fixations corresponds to the total number of fixations before  
526 leaving the word. Total Fixation Duration is the sum of all fixation durations starting  
527 with the first fixation on the word and ending with the first forward saccade towards  
528 the digit. Total reading time thus includes both first-pass fixation durations and the  
529 duration of within-word short regressions. The experimental paradigm prevented the  
530 occurrence of long regressions since the participants were instructed to read the word  
531 then the digit and press the key to start the next trial as soon as possible. Single  
532 fixation duration is measured on words that received only one fixation during read-  
533 ing. The two last measures are taken from words that received only two fixations.  
534 The durations of the first and second of two fixations were separately analyzed. Most  
535 previous studies (e.g., Pagan & Nation, 2019) that distinguished single fixation trials  
536 from multiple fixation trials focused on the analysis of the first-of-multiple fixation

**Table 2.** Number and percentage of trials per item type and exposure (in columns: W for words, PW for pseudo-words, and exp1 to exp5 for the five exposures) and number of fixations (in rows). The total indicates the number and the percentage of trials kept after removing outliers.

	Size	PW exp1	PW exp2	PW exp3	PW exp4	PW exp5	W exp1	W exp2	W exp3	W exp4	W exp5
1 fixation	N	152	149	145	76	91	382	313	310	163	160
	%	12.1	17.7	17.3	18.1	21.7	30.3	37.3	36.9	38.8	38.1
2 fixations	N	358	288	318	173	173	515	346	351	179	177
	%	28.4	34.3	37.9	41.2	41.2	40.9	41.2	41.8	42.6	42.1
3 fixations	N	276	176	175	84	74	186	83	80	35	38
	%	21.9	21.0	20.8	20.0	17.6	14.8	9.9	9.5	8.3	9.0
4 fixations	N	168	86	71	35	25	48	22	22	8	9
	%	13.3	10.2	8.5	8.3	6.0	3.8	2.6	2.6	1.9	2.1
≥ 5 fixations	N	138	50	50	22	14	29	16	8	4	3
	%	11.0	6.0	6.0	5.2	3.3	2.3	1.9	1.0	1.0	0.7
<b>Total</b>	N	1092	749	759	390	377	1160	780	771	389	387
	%	86.7	89.2	90.4	92.9	89.8	92.1	92.9	91.8	92.6	92.1

537 while ignoring the number and duration of subsequent fixations. We here decided to  
 538 restrict the analysis to a more homogeneous corpus of trials, considering trials with  
 539 exactly one or two fixations. As shown on Table 2, two-fixation trials predominated in  
 540 the corpus, representing 38.9 % and 45.0 % trials on pseudo-words and words respec-  
 541 tively. Focusing on two-fixation trials allowed an in-depth analysis of both the first and  
 542 second fixation duration. Further analyses were run using the first-of-multiple fixation  
 543 duration measure. Results were identical to those reported for the first-of-two-fixation  
 544 duration, except when otherwise reported in the text.



**Figure 2.** Eye movement measures recorded during the reading task as a function of the number of exposures. (A) Number of fixations, (B) Total Fixation duration, (C) Single fixation duration, (D) First-of-two fixation duration and (E) Second-of-two fixation duration. All times are in ms and vertical bars are for standard errors.

545 For all eye movement measures, results are provided for the target pseudo-words  
 546 and the control words as a function of the number of exposures. A differential exposure  
 547 effect for the target pseudo-words and control words was expected as a marker of new  
 548 word orthographic learning. As performance on memorization tasks provided evidence



549 for effective orthographic learning occurring across the first three exposures, we were  
550 in particular attentive to differences in oculomotor measures between the first and  
551 second or third exposure.

552 **3.3.1.1. Number of fixations.** As shown on Figure 2(A), the number of fixa-  
553 tions recorded during the reading phase varied depending on item type (main ef-  
554 fect:  $\beta = -0.66$ ,  $z = -11.69$ ,  $p < .001$ ) and number of exposures (main effect:  
555  $\beta = 0.11$ ,  $z = 8.16$ ,  $p < .001$ ). More importantly, the item-type by number-of-  
556 exposure interaction was significant ( $\beta = -0.09$ ,  $z = -3.39$ ,  $p < .001$ ), showing  
557 a steeper decrease in number of fixations across exposures for pseudo-words than  
558 for words. Post-hoc analyses showed that the number of fixations more sharply de-  
559 clined for the pseudo-words than for words between the first and second exposures  
560 ( $\beta = 0.21$ ,  $z = 2.15$ ,  $p = .032$ ; non significant interaction between the second and  
561 third exposure:  $\beta = 0.02$ ,  $z = 0.17$ ,  $p = .868$ ).

562 **3.3.1.2. Total Fixation Duration.** Total Fixation Duration for target pseudo-  
563 words and control words, as a function of the number of exposures, is plotted in  
564 Figure 2(B). The two main effects of item-type ( $\beta = -209.76$ ,  $t = -26.14$ ,  $p < .001$ )  
565 and number-of-exposures ( $\beta = 29.47$ ,  $t = 14.77$ ,  $p < .001$ ) were significant, as well  
566 as the interaction between these two factors ( $\beta = -31.33$ ,  $t = -11.04$ ,  $p < .001$ )  
567 showing steeper total fixation duration decrease with increased exposure for pseudo-  
568 words than for words. Post-hoc analyses showed a sharper total fixation duration  
569 decline for pseudo-words than for words between the first and second exposures ( $\beta =$   
570  $68.96$ ,  $t = 12.16$ ,  $p < .001$ ) as well as between the second and third exposure ( $\beta =$   
571  $37.73$ ,  $t = 5.10$ ,  $p < .001$ ).

572 **3.3.1.3. Fixation Duration in Single Fixation Trials.** The analysis of single  
573 fixation duration according to item-type and number-of-exposures was performed on  
574 the 1,941 trials (25.7 % of data) having a single fixation (see Table 2 for details). Results  
575 are presented in Figure 2(C). The analysis showed longer single fixation duration for  
576 pseudo-words than for words ( $\beta = -77.85$ ,  $t = -7.11$ ,  $p < .001$ ) and a significant main  
577 duration decrease across exposures ( $\beta = 18.00$ ,  $t = 5.54$ ,  $p < .001$ ). The item-type by  
578 number-of-exposure interaction was significant ( $\beta = -16.03$ ,  $t = -3.08$ ,  $p = .002$ ),  
579 suggesting that the duration of single fixations decreased more sharply for pseudo-  
580 words than for words across exposures. Local interaction analyses reveal a similar  
581 decrease of fixation duration for words and pseudo-words between the first and second  
582 exposure ( $\beta = -21.11$ ,  $t = -1.27$ ,  $p = .204$ ) but a sharper decrease on target pseudo-  
583 words between the second and third exposure ( $\beta = 52.76$ ,  $t = 3.34$ ,  $p < .001$ ).

584 **3.3.1.4. Fixation Duration in Two-Fixation Trials.** Two-fixation trials rep-  
585 resent 2,878 trials or 38.1 % of data (see Table 2 for details). Figure 2(D) and Fig-  
586 ure 2(E) illustrate the number-of-exposure effect on target pseudo-words and control  
587 words for the first and second fixation of the two-fixation trials respectively. Results  
588 showed that the first-of-two fixation duration lasted longer for pseudo-words than  
589 for words ( $\beta = -80.53$ ,  $t = -11.47$ ,  $p < .001$ ) and duration decreased across ex-  
590 posures ( $\beta = 12.98$ ,  $t = 6.15$ ,  $p < .001$ ). The item-type by number-of-exposure  
591 interaction was significant ( $\beta = -9.53$ ,  $t = -2.98$ ,  $p = .003$ ) suggesting a sharper  
592 decrease of the first-of-two fixation duration for pseudo-words than for words. Post-

593 hoc analyses showed that none of the local interactions between the first and second  
594 ( $\beta = 17.73$ ,  $t = 1.61$ ,  $p = .108$ ) or second and third ( $\beta = 12.82$ ,  $t = 1.30$ ,  $p = .193$ )  
595 exposure was significant.

596 Analysis of the second-of-two fixation duration showed a main effect of item-type  
597 ( $\beta = -72.65$ ,  $t = -10.72$ ,  $p < .001$ ) and number-of-exposures ( $\beta = 11.83$ ,  $t =$   
598  $6.67$ ,  $p < .001$ ), and a significant interaction between item-type and number-of-  
599 exposures ( $\beta = -9.49$ ,  $t = -3.59$ ,  $p < .001$ ). However, there was a significant local  
600 interaction between the first and second exposure ( $\beta = 52.88$ ,  $t = 5.93$ ,  $p < .001$ )  
601 but not between the second and third exposure ( $\beta = -9.89$ ,  $t = -0.96$ ,  $p = .338$ ),  
602 showing sharper decline of the second-of-two fixation duration between the first two  
603 exposures to target pseudo-words.

### 604 **3.4. Analysis of potential VA Span Effect**

605 We further evaluated the potential influence of the participants' VA span abilities  
606 on orthographic learning (spelling-to-dictation and orthographic decision) and eye  
607 movement measures for target pseudo-words. For this purpose, participants were split  
608 into two groups with higher or lower VA span, using the median value (see Equation 1  
609 for  $TS_{VAS}$  calculation;  $TS_{VAS}(med) = 79\%$ ;  $TS_{VAS}(mean) = 78.3\%$ ;  $TS_{VAS}(SD) =$   
610  $8.0\%$ ). The two groups were characterized by a mean VA span performance of 71.8 %  
611 (SD = 4.6 %) and 84.8 % (SD = 4.7 %) respectively. Results from all tasks as a  
612 function of VA span Group are provided in Supplementary Material (see "Appendix"  
613 file).

614 We first checked whether orthographic learning was more effective depending on  
615 the participants' VA span. Results from the spelling-to-dictation task revealed no  
616 significant Group effect on any of the two measures of whole word ( $\beta = -0.26$ ,  $z =$   
617  $-1.20$ ,  $p = .230$ ) and by-grapheme accurate spellings ( $\beta = -0.07$ ,  $t = -0.75$ ,  $p =$   
618  $.456$ ). There was no significant interaction between the Group and the Number of  
619 Exposure for either the whole pseudo-word ( $\beta = 0.28$ ,  $z = 1.37$ ,  $p = .172$ ) or by-  
620 grapheme spellings ( $\beta = 0.01$ ,  $t = 0.18$ ,  $p = .855$ ). Similarly, no significant Group  
621 effect ( $\beta = -0.03$ ,  $z = -0.19$ ,  $p = .853$ ) and no interaction ( $\beta = -0.10$ ,  $z =$   
622  $-0.59$ ,  $p = .557$ ) were found in orthographic decision accuracy. However, there was a  
623 significant VA span Group effect on RTs ( $\beta = 234.13$ ,  $t = 11.54$ ,  $p < .001$ ). The higher  
624 the participants' VA span score, the shorter the RTs. The VA span Group by Number  
625 of Exposure interaction was significant ( $\beta = -44.60$ ,  $t = -2.54$ ,  $p = .011$ ) but none  
626 of the local interactions (all  $ps > .05$ ), suggesting sharper decrease of orthographic  
627 decision RTs across exposures for participants with higher VA span.

628 For eye movements, there was a significant main effect of VA span group on all the  
629 eye movement measures, except the number of fixations ( $\beta = 0.23$ ,  $z = 1.69$ ,  $p =$   
630  $.091$ ). The total fixation duration was significantly shorter for the higher VA span  
631 group ( $\beta = 101.33$ ,  $t = 15.01$ ,  $p < .001$ ). The main effect of VA span Group on  
632 the duration of fixations in single ( $\beta = 60.02$ ,  $t = 2.10$ ,  $p = .036$ ) and two fixation  
633 (first-of-two fixation:  $\beta = 42.53$ ,  $t = 2.52$ ,  $p = .012$ ; second-of-two fixation:  $\beta =$   
634  $41.02$ ,  $t = 2.66$ ,  $p = .008$ ) trials was also significant, showing shorter durations in the  
635 group with higher VA span. However, none of the Group by Exposure interaction was  
636 significant (all  $ps > .05$ ), suggesting that the two VA span groups showed very similar  
637 decrease in fixation duration over exposures. Note that the analyses using VA span as  
638 a continuous variable revealed a significant VA span by Exposure interaction, but only  
639 for the second-of-two fixation duration that decreased more sharply for participants

640 with higher VA span ( $\beta = -0.30$ ,  $t = -2.01$ ,  $p = .044$ ).

#### 641 4. Discussion

642 In this study, we investigated orthographic learning of new words using eye-tracking.  
643 Through a paradigm inspired from the self-teaching paradigm initiated by Share  
644 (1999), French-speaking skilled readers were exposed to novel words, presented in  
645 isolation for one, three or five exposures. A conventional spelling-to-dictation task and  
646 an original orthographic decision task were used to measure orthographic learning af-  
647 ter the reading phase. Further, VA span tasks were administered to investigate the  
648 potential impact of visual attention capacity on the processing of new words while  
649 reading and as a result, on the orthographic learning process.

650 Evidence from the two memorization tasks and eye-movement measures is in line  
651 with previous reports, suggesting that the paradigm we used was appropriate to ex-  
652 plore orthographic learning. Such evidence is threefold. First, results from the offline  
653 orthographic memorization tasks – higher number of target graphemes in pseudo-word  
654 spelling and shorter RTs in orthographic decision– suggest that orthographic learn-  
655 ing began very early during processing, namely across the three first exposures to the  
656 novel word. Fast orthographic learning is convergent with findings in previous research  
657 (Nation et al., 2007; Share, 2004).

658 Second, in line with the previous eye-tracking studies that compared word and  
659 pseudo-word processing (Lowell & Morris, 2014; Rayner, 2009), we show that the  
660 number of fixations is higher for pseudo-words than for words. As previously reported  
661 by Pellicer-Sanchez (2016), the item-type effect is quite consistent across exposures  
662 and extends to all the eye movement measures. Third, we show that the higher the  
663 number of exposures to the target pseudo-word, the lower the processing time. There  
664 is strong agreement that visual processing of a new word is influenced by the number  
665 of encounters with this word (Joseph & Nation, 2018; Joseph et al., 2014). However,  
666 variations in the oculomotor measures carried out on real words also suggest some  
667 sensitivity to the number of exposures. Given the range of frequency of our control  
668 words, it seems difficult to assimilate these variations to any orthographic learning.  
669 This effect may be more likely due to repeated reading of the same set of well-known  
670 words in a short time, inducing familiarization to the set of stimuli through repetition.  
671 If that were the case, such a process could also account for some of the variations  
672 of the oculomotor measures for the pseudo-words. The use of control words is thus  
673 critical to disentangle repetition effects from learning effects. Comparison of exposure  
674 effects on words and pseudo-words in the current study revealed higher decrease in  
675 processing time – as evidenced by the number of fixations and total fixation duration–  
676 over exposures for pseudo-words than for words. This finding clearly shows that a  
677 repetition effect cannot account alone for the oculomotor behavior observed on pseudo-  
678 words. Evidence for differential processing time during pseudo-word processing attests  
679 that decreased processing time with increasing exposures does reflect orthographic  
680 learning. In the following, we focus on the novelty of the current findings, underlying  
681 the relevance of the orthographic decision task and exposure-by-exposure track of eye-  
682 movements during the learning phase to reveal orthographic learning. We last discuss  
683 how VA span influences the learning process.

684 **4.1. *The measures of orthographic learning***

685 A first main contribution of the current study is to provide novel ways of measuring  
686 orthographic learning. Based on previous work of Wang et al. (2011), Tamura et al.  
687 (2017) and Wang et al. (2013), we designed a new orthographic decision task as an  
688 alternative to the standard but more debated task of orthographic choice (Castles &  
689 Nation, 2008; Tucker et al., 2016). Instead of using a multiple choice paradigm as  
690 in the standard task, targets and homophonic foils were presented one-at-a-time to  
691 prevent strategic influences, like responses based on phonological and/or orthographic  
692 comparison. It was assumed that the processing of isolated items, targets or foils, in  
693 orthographic decision would more directly trigger the recognition system and would  
694 increase sensitivity to orthographic learning. Current evidence suggests that the novel  
695 orthographic decision task likely reflects orthographic learning. First, better and faster  
696 target pseudo-word recognition was reported across exposures. Second, reported effects  
697 on both accuracy and RTs between the first and third exposure suggest good task  
698 sensitivity to the early steps of orthographic learning. Last, significant changes between  
699 the third and fifth exposures suggests sensitivity all along the learning process. The  
700 orthographic decision task thus appears as a promising offline alternative to track the  
701 evolution of implicit learning during reading. Whether the novel orthographic decision  
702 task challenges the widely used orthographic choice task warrants further investigation,  
703 through direct comparison of performance in the two tasks. Future studies would  
704 further explore whether the orthographic decision paradigm is appropriate to measure  
705 orthographic learning in children.

706 Orthographic learning was further assessed in our adult participants through a  
707 spelling-to-dictation task. As previously reported for children (Bosse et al., 2015; Cun-  
708 ningham, 2006), the task was difficult even for adult participants who showed relatively  
709 low performance when considering the number of target pseudo-words that were accu-  
710 rately spelled as a whole. Although spelling performance significantly improved after  
711 five exposures, only about a quarter of the pseudo-words were accurately spelled. This  
712 suggests that memorization of the perfect whole spelling of a new 8-letter word is  
713 a long process that is not completed after five exposures to the new written form.  
714 However, the fact that more target graphemes were accurately spelled after three ex-  
715 posures to the pseudo-words provides evidence of early orthographic learning. This  
716 finding suggests that orthographic representations of the novel words become more  
717 and more precise over exposures, even if the exact pseudo-word spelling is not yet sta-  
718 bilized after five encounters. Overall, the spelling-to-dictation task seems appropriate  
719 to explore orthographic learning in adult participants and task sensitivity is improved  
720 when using a fine-grain scoring based on target graphemes.

721 **4.2. *Exposure-by-exposure time course of orthographic learning***

722 A second main contribution of our work is to provide insights on the time course of  
723 orthographic learning through the exposure-by-exposure analysis of eye movements  
724 during the learning phase. Although changes in eye movements across different phases  
725 of repeated print exposure to novel words were examined in previous research (Joseph  
726 & Nation, 2018; Joseph et al., 2014), our study is one of the very first (Pellicer-Sanchez,  
727 2016) to provide an exposure-by-exposure, in-depth analysis of this online process. The  
728 current findings suggest such analysis is particularly relevant and informative. While  
729 the offline measures of orthographic memorization suggest relative quick learning of  
730 the novel words (after only a few exposures), the exposure-by-exposure exploration of

731 the learning process likely highlights very early evidence of orthographic learning. Such  
732 exploration further allows investigating whether and how the different eye movement  
733 measures respond to additional exposures during incidental learning.

734 The analysis of eye movements in our adult participants revealed early changes  
735 with additional exposure on the three measures of number of fixation, second of two  
736 fixation duration and single fixation duration. A sharper duration decline was observed  
737 between the first and second exposure to the novel word for the two former measures  
738 and between the second and third exposure for the latter. As a direct consequence,  
739 a sharp decrease of total fixation duration was observed between both the first and  
740 second, and second and third exposures. Thus, specific changes in time processing for  
741 pseudo-words that can be attributed to orthographic learning occur during the very  
742 first stages of the learning process. These findings support prior evidence of rapid  
743 orthographic learning (Cunningham, 2006; Share, 2004). Robust learning starts after  
744 just one exposure not only in transparent languages as Hebrew (Share, 2004) but also  
745 in non transparent languages as English (Cunningham, 2006) or French (current data).  
746 Rapid and automatic orthographic learning thus appears as a property of the learning  
747 system that is independent of language transparency. Current findings further confirm  
748 that early orthographic learning can occur in the absence of semantic context (Landi  
749 et al., 2006; Nation et al., 2007).

750 Another originality of the current work was to capitalize on the predominance of  
751 two fixation trials for an analysis of both the first and second fixation in conditions  
752 where novel words were fixated twice and only twice. Most previous studies in the  
753 field analyzed the duration of the first of multiple fixations without providing insights  
754 on later processing (Bertram, 2011), see however Mousikou and Schroeder (2019) for  
755 an attempt in an eye tracking study on morphological processing. An analysis of the  
756 first-of-multiple fixation duration was actually carried out in the present study; results  
757 were not reported here as they were very similar to those reported for the first-of-two  
758 fixation. Focusing on two fixations trials revealed an effect of orthographic learning not  
759 only on the first-of-two fixation duration but further on the duration of the second-of-  
760 two fixation.

761 Interestingly, only the second fixation duration showed a sharp decrease between  
762 the first and the second exposure. In contrast, the duration of the first fixation gradu-  
763 ally declined across exposures without any specific effect emerging from the first three  
764 encounters with the novel word. In this regard, the first-of-two-fixation duration mea-  
765 sure differs from the other eye-movement measures that all showed earlier significant  
766 changes. Although further studies are needed to check the robustness of this finding  
767 and better understand why orthographic learning may rapidly affect the duration of  
768 the second- but not the first-of-two fixation, a potential sketch emerges from the over-  
769 all data. At the first encounter, thus in the absence of lexical representation, only a  
770 few pseudo-words (12 %) were processed within a single fixation, suggesting that, for  
771 most pseudo-words, only insufficient or partial letter identity information could be  
772 extracted within a unique fixation. As previously suggested (Lowell & Morris, 2014),  
773 long processing time for pseudo-words at the first encounter is likely to reflect time  
774 needed for bottom-up information extraction on letter identity and for encoding the  
775 new letter-string into memory. As a result, the large variation observed in number  
776 of fixations and processing time between the first and second exposure may primarily  
777 reflect improved letter identification at the second exposure, due to top-down influence  
778 from the newly acquired orthographic representation. However, top-down information  
779 at the second encounter was not sufficient to significantly decrease single fixation du-  
780 ration, and such a decrease was only observed between the second and third exposures.

781 As for the number of fixations, very early decrease in duration for the second-of-two  
782 fixation suggests that this measure is particularly sensitive to the existence of a newly  
783 created orthographic representation of the pseudo-word, which is not the case for the  
784 first-of-two-fixation duration. This might suggest that the second-of-two fixation, that  
785 was required to complete letter identity processing during orthographic encoding at  
786 the first encounter, would be mainly used later on and from the second exposure to  
787 check matching with the newly created representation. In contrast, the first-of-two  
788 fixation may be empowered to progressively evolve into being a single fixation. More  
789 and more letters are likely to be processed more efficiently, thus faster, during this  
790 first fixation as the quality of orthographic representation improves across exposures.  
791 Overall, the exposure-by-exposure analysis of eye movements during the learning  
792 phase appears as particularly useful to better understand the critical links between  
793 eye-movement patterns and the orthographic learning process. However, the current  
794 findings suggest that independent analyses of how the different eye-movement measures  
795 evolve over exposures provides only piecemeal information on the learning process. In  
796 particular, we lack a dynamic model providing insights on how the number of fixations  
797 and fixation duration interacts during orthographic learning. Moreover, contrary to  
798 previous research that minimized the impact of visual processing on learning (Perry  
799 et al., 2019; Pritchard et al., 2018; Share, 1999; Ziegler et al., 2014), current findings  
800 clearly argue for a major role of visual processing on new orthographic knowledge  
801 acquisition.

#### 802 *4.3. Does VA span affect orthographic learning?*

803 Another novelty of the current study was to explore whether differences in VA span  
804 do affect orthographic learning. For this purpose, our set of participants was split  
805 into two groups with higher or lower VA span skills. Comparison of the two groups'  
806 performance on the offline measure of orthographic decision revealed that adult readers  
807 with a higher VA span recognized novel word spellings faster than their lower VA span  
808 peers. More importantly, RTs were found to decline more steeply across exposures in  
809 the higher VA span group, suggesting higher improvement of recognition skills with  
810 additional exposures in this group. The higher VA span group further showed shorter  
811 processing times on all the fixation duration measures, but the number-of-exposure  
812 effect on processing time was similar in the two groups. However, the analysis using VA  
813 span as a continuous variable revealed that the duration of the second-of two fixation  
814 more sharply declined across exposures in participants with higher VA spans.

815 A more unexpected finding is the absence of VA span group effect on the number of  
816 fixations during target pseudo-word processing. A relationship between VA span and  
817 the number of fixations was previously reported (Prado et al., 2007). We thus expected  
818 adult participants with lower VA span abilities to process fewer letters simultaneously  
819 at each fixation, which should have resulted in more fixations. However, previous evi-  
820 dence that the number of fixation varied depending on VA span abilities was reported  
821 in dyslexic children with a VA span deficit, while our participants have no history of  
822 dyslexia and no VA span deficit. As expert readers, they were probably able to process  
823 enough letters at each fixation whatever the variations in their VA span.

824 The role of VA span in orthographic learning requires further investigations. Nev-  
825 ertheless, the current findings suggest that the amount of visual attention available  
826 for multiletter simultaneous processing may increase the quality of novel word ortho-  
827 graphic representations that will be established in memory. The rationale for such

828 an assumption is that the more attention is allocated to the novel word, the faster  
829 is letter identity processing, which boosts relevant letter information encoding and  
830 facilitates orthographic learning. In line with this assumption, there is evidence that  
831 participants with higher VA spans show faster processing time from the first encounter,  
832 thus faster letter identity processing and faster orthographic encoding. However, if re-  
833 lated to more efficient orthographic learning, processing time should decrease more  
834 sharply over exposures in participants with higher than lower VA span. There is some  
835 evidence that this might be the case for the second-of-two-fixation duration but not  
836 for the other measures of total fixation duration, single fixation duration or first-of-  
837 two-fixation duration. Thus, VA span might more specifically affect the processing  
838 time measure that was previously found to be the most sensitive to early orthographic  
839 learning. If higher VA span abilities do contribute to stabilize more precise ortho-  
840 graphic representations of the pseudo-words across exposures, we would expect more  
841 pseudo-words to be processed through a single fixation over time. In agreement with  
842 this expectation, post-hoc analyses revealed that participants with higher VA span  
843 abilities processed more pseudo-words in a single fixation after five encounters<sup>2</sup>. Ev-  
844 idence from second-of-two-fixation duration and single fixation trials suggest better  
845 quality of orthographic representations in the higher VA span group, which might  
846 account for faster recognition of pseudo-word spellings over exposures in the ortho-  
847 graphic decision task. We would further expect better learning to progressively affect  
848 recognition accuracy in orthographic decision and pseudo-word spelling performance.  
849 Such effects were not observed after five exposures and might require a higher number  
850 of exposures to the target pseudo-words. Assuming that higher VA span contributes  
851 to improve orthographic learning would further predict a relationship between VA  
852 span performance and lexical orthographic knowledge. Post-hoc correlation analysis  
853 supports this relationship, showing that the higher the VA span, the higher was the  
854 number of irregular words that were accurately spelled by our participants (Pearson's  
855 correlation = 0.31,  $p = .044$ ). Overall, the current study provides a number of tiny  
856 but convergent evidence that the amount of visual attention available for novel word  
857 processing may contribute to orthographic learning. While the current findings align  
858 with previous evidence that readers with higher VA span read faster (Antzaka et al.,  
859 2017; Bosse & Valdois, 2009; Lobier et al., 2013), show lower length effects in real  
860 word reading (van den Boer et al., 2013) and have better spelling performance (van  
861 den Boer et al., 2015), further studies are required to comfort and clarify the role of  
862 VA span in orthographic learning.

863 Evidence for a potential contribution of visual attention span to orthographic learn-  
864 ing would have strong practical and theoretical implications. At the practical level, in-  
865 tensive training using VA span targeted intervention programs, like COREVA (Valdois  
866 et al., 2014) or MAEVA (Zoubinetzky et al., 2019), has proven successful to improve  
867 VA span with positive transfer to reading performance. Further research is required  
868 to explore whether similar trainings may further improve orthographic learning skills  
869 and, as a consequence, spelling performance. Evidence that VA span contributes to  
870 orthographic learning should further have implications for models of learning to read.  
871 Current models (Pritchard et al., 2018; Ziegler et al., 2014) emphasize the impact  
872 of phonological decoding on orthographic learning while minimizing the role of vi-

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<sup>2</sup>Post-hoc analyses of variance (ANOVAs) showed that the Group-by-Exposure interaction on the number of single fixation trials was not significant ( $F(1, 40) = 3.23$ ,  $p = .080$ ,  $\eta^2 = .075$ ). However, contrast analyses revealed a higher rate of single fixation trials in the higher than lower VA span Group at the fifth encounter (15.38% vs. 8.75%,  $F(1, 40) = 5.18$ ,  $p = .028$ ,  $\eta^2 = .115$ ), while no significant difference between groups was found at the first encounter (7.69% vs. 6.23%,  $F(1, 40) = 0.85$ ,  $p = .361$ ,  $\eta^2 = .021$ ).

873 visual processing in this learning process. As acknowledged by Pritchard et al. (2018),  
874 these models do not incorporate the sophisticated mechanisms of visual processing  
875 postulated by word recognition models, as the gradient of acuity (Whitney, 2001),  
876 lateral interferences (Davis, 2010; Gomez et al., 2008) or a visual attention component  
877 (Ans et al., 1998; Ginestet et al., 2019; Mozer & Behrmann, 1990). Evidence that vi-  
878 sual attention contributes to orthographic learning would require the development of  
879 new models including both well-defined processes of phonological decoding, and fully  
880 specified mechanisms of visual processing, including a visual attention mechanism.  
881 Furthermore, while current models adopt a one-shot approach to learning, creating a  
882 fully specified orthographic word node after only a single exposure, current eye move-  
883 ment data rather suggest that orthographic learning is a gradual process that extends  
884 over multiple exposures. A challenge for future orthographic learning and reading ac-  
885 quisition models is to better fit the human data that describes the online dynamics of  
886 the learning process.

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891 tions”.

## 892 **Conflict of Interest Statement**

893 The authors declare that the research was conducted in the absence of any commercial  
894 or financial relationships that could be construed as a potential conflict of interest.

## 895 **Appendix A. Lists of items**

- 896 (1) Pseudo-words used in the learning phase, the spelling-to-dictation of pseudo-  
897 words and the orthographic decision: List A: broufand, chaiquau, deinrint, fain-  
898 gion, gouciant, nauplois, ploirtart, quinsard, speirain, tramoint; List B: ceitteau,  
899 chanquet, coirtint, drottont, flommais, glounein, priquoin, quarlant, siampoie,  
900 trimpond; List C: bussiond, cherrein, cercard, claffand, fentroit, phacrait, prin-  
901 nant, scrodain, tauppart, trancare
- 902 (2) Control words used in the learning phase: List A: uniforme, portrait, enceinte,  
903 mouchoir, surprise, complice, scandale, chanteur, immeuble, avantage; List B:  
904 physique, revanche, horrible, boutique, sensible, fauteuil, chocolat, mensonge,  
905 solution, voyageur; List C: prochain, grandeur, nocturne, lointain, religion, em-  
906 pereur, division, quartier, province, jugement
- 907 (3) Homophones used in the orthographic decision: broufant, cheicaud, dainrein,  
908 phingion, goussion, nopploie, ploittar, quainsar, spairint, trammoin, saitteau,  
909 chenquai, quoirin, drautond, flaummet, glounnin, pricoint, quarland, siempoint,  
910 trimppon, busciont, chairain, siercart, claphant, phantroi, phacrais, prinnand,  
911 scraudin, thauppar, trenquar



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