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**Orthographic Learning and Transfer of Complex Words: Insights from Eye-Tracking
During Reading and Learning Tasks**

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To download Supplementary Material files (data, statistical models and appendix), please use this link: https://osf.io/jpbnz/?view_only=289450b9cf1f40efad6aec751b6b0a20

Abstract

Background: Efficient word identification is directly tied to strong mental representations of words, which include spellings, meanings, and pronunciations. Orthographic learning is the process by which spellings for individual words are acquired.

Methods: In the present study, we combined the classic self-teaching paradigm with eye-tracking to detail the process by which complex pseudowords are learned. With this methodology, we explored the visual processing and learning of complex pseudowords, as well as the transfer of that learning. We explore visual processing across exposures during the initial reading task and then measure learning and transfer in orthographic choice and spelling tasks.

Results: Online eye movement monitoring during the repeated reading of complex pseudowords revealed that visual processing varied across exposures with key differences based on word type. Further, data from both dictation and eye movements recorded during the orthographic choice task suggested stronger learning of morphologically than orthographically complex pseudowords after four encounters. Finally, results suggested that learning transfer occurred, with similar levels of accurate recognition of new pseudowords that were morphologically or orthographically related to pseudowords learned during the reading phase than of new pseudowords never read.

Conclusions: The present study provides new insights into theory and methodological discussions of orthographic learning.

Keywords: orthographic learning, morphology, transfer of learning.

Implications for Practice

What Is Already Known About This Topic

- Children and adults learn new words through their reading, an effect robustly demonstrated through the self-teaching paradigm.
- Recent research shows that children transfer their learning of new words to that of other words, with little consensus as to how this happens.

What This Paper Adds

- In this study, we evaluate in detail the process of this learning by combining behavioral assessed with the classic self-teaching paradigm with eye movement monitoring. Eye movement monitoring during repeated exposures to pseudowords revealed differences in eye movements between morphologically and orthographically complex pseudowords suggesting differences in visual processing during learning itself.
- Evidence of stronger learning for the spellings of morphologically complex pseudowords emerged from both behavioral and eye movement data.
- We found that learning transferred to new pseudowords, and did so to a similar extent whether they were morphologically or orthographically related to learned pseudowords.

Implications For Theory, Policy Or Practice

- Methodologically, we demonstrate the value of including eye-tracking to evaluate orthographic learning in a self-teaching paradigm, both during reading itself and during later processing. Our findings confirm the effectiveness of this technique to investigate orthographic learning and learning transfer.
- The self-teaching hypothesis is the most popular theoretical model of orthographic learning, predictions of which have been questioned in recent studies. Through this study, we provide fresh empirical tests of the cognitive mechanisms in this model, specifying current models of reading.

1 Efficient word identification is directly tied to strong mental representations of words,
2 which include spellings, meanings and pronunciations (Ehri, 2005; Perfetti, 2007). Orthographic
3 learning is the process by which these representations for individual words are acquired (Share,
4 2008). The Self-Teaching Hypothesis suggests that new words are learned through phonological
5 recoding, a built-in teaching mechanism, enabling the learning of individual words with exposure
6 to each word directly tied to its learning (Share, 1995). With accumulated reading experience,
7 the phonological recoding process is predicted to include morphemic constraints (Share, 1995;
8 2008), leading to the prediction that new words will be differentially processed as they are read
9 based on morphological structure. In the present study, we use the self-teaching paradigm (Share,
10 1999) to test the potential effects of morphological structure on the visual processing and
11 learning of new words. We also explore the potential transfer of this learning, testing the strong
12 prediction that learning of each word is tied to exposure to that precise word (Share, 1995).

13 Our first question lies in whether there are effects of morphological structure in the visual
14 processing of new words across exposures – effectively during learning. Standard self-teaching
15 paradigms involve participants reading four instances of a new word in a story, and they
16 typically assess the outcome of this processing with measures of learning such as an orthographic
17 choice task (Share, 1999; see Tucker et al., 2016 for a recent example). Several studies have
18 demonstrated that learning is more effective with increasing exposures (e.g., Share, 1999),
19 including in studies combining both behavioral measures with eye-tracking. For instance, Joseph
20 et al. (2014) found that participants fixated on and viewed new words for less time with more
21 exposures and Li et al., (2019) reported decreases in the number of fixations (as well as
22 regressions back to) across encounters (see also Ginestet et al., 2020). It seems that processing
23 might become increasingly efficient across exposures. In the present study, we build on this work

24 to explore the novel question of whether the visual processing of morphologically complex and
25 orthographically complex (yet morphologically simple) pseudowords differs across exposures to
26 them in story reading.

27 We use eye-tracking to explore this question. Applying eye-tracking encouraged us to
28 study three-morpheme pseudowords because it enabled us to explore visual processing in finer
29 detail within words, while also considering processing of greater morphological complexity than
30 in prior studies. Eye-tracking has been used recently in other studies of orthographic learning of
31 novel words, albeit addressing other factors (e.g., Joseph et al., 2014; Joseph & Nation, 2018; Li
32 et al., 2019). Available research applying eye-tracking to the study of morphological complexity
33 tends to use known words. In a study examining English speaking adults' reading of words
34 embedded in short sentences, Inhoff et al. (1996) found that gaze durations and first fixation
35 durations were longer on compound words than on suffixed and monomorphemic words, which
36 did not significantly differ with each other. Similarly, Yan et al. (2014; see also Hyönä et al.,
37 2018) found that gaze durations and first fixation durations increased with morphological
38 complexity during the reading of Uighur words presented in sentences. Further, initial landing
39 positions were closer to the beginning of morphologically complex than simple words (Yan et
40 al., 2014). Together these studies of known words, suggest that morphological complexity
41 sometimes makes visual processing of words more difficult, requiring longer fixation durations.
42 Turning to one of the few prior studies of pseudowords, Breadmore and Carroll (2018)
43 investigated the visual processing of pseudowords (i.e., existing verbs containing an error) read
44 in sentences by native speakers. English-speaking adults had longer reading times for
45 morphologically complex pseudowords (over-regularizations) than for the correct verb forms.
46 More interestingly, they reported shorter total fixation duration for morphologically complex

47 pseudowords than for monomorphemic pseudohomophones suggesting that morphological
48 structure might aid visual processing of pseudowords. Regardless of the direction of effects,
49 these studies indicate the insight looking at eye movements can provide into the influence of
50 morphological structure on processing.

51 Our second research question is whether there might be stronger learning for
52 morphologically than for orthographically complex pseudowords following on the reading
53 experience. To date, there are conflicting findings from diverging methods. In the single
54 available study on the learning of new words. Tucker and colleagues (2016) studied learning of
55 orthographically and morphologically complex pseudowords (e.g., *feaple* and *feaper*,
56 respectively) within a self-teaching paradigm. In this between-subjects manipulation, Tucker et
57 al. (2016) found that children in Grades 3 and 5 learned the spellings of morphologically and
58 orthographically complex pseudowords to a similar extent, based on parity in levels of success
59 on an orthographic choice task.

60 In contrast, two studies of similarly aged French-speaking children found that the presence
61 of morphologically related words along with a base form enabled stronger learning of the base
62 form in contrast to control conditions that include multiple presentations without clear
63 morphological relations (Pacton et al., 2018; see also Pacton et al., 2013). Pacton et al. (2018)
64 suggested that the presence of morphological information during the process of orthographic
65 learning improved the outcome of this learning. That said, this study contrasted the type of words
66 presented in the learning context (e.g., the kinds of words in the stories), rather than the
67 morphological structure of the words that the children were tested on. Nevertheless, these results
68 align with studies of known words showing that children learn morphologically complex words
69 better than those without such a structure, both in terms of greater accuracy and speed in their

70 reading and spelling (e.g., *turning* versus *turnip*; Deacon & Dhooge, 2010; Deacon et al., 2011).
71 Given the conflicting findings to date on the effect of morphological structure on the learning of
72 words, we explore it here by examining the impact of pseudoword morphological structure on
73 performance during spelling and orthographic choice tasks.

74 Our third and final question lies in whether readers transfer their learning and whether this
75 is influenced by morphological structure. Tucker et al (2016) suggested that learning of one
76 pseudoword transfers to other newly encountered pseudowords, contrasting with Share's (1995)
77 initial predictions of item-by-item learning. Tucker et al., (2016) found that English-speaking
78 children were equally likely to transfer their learning of pseudowords read in short stories (e.g.,
79 *feap*) to other pseudowords that were morphologically related, as to those that simply shared the
80 same orthographic structure (e.g., *feaper* and *feaple*). These effects emerged in an orthographic
81 choice task and suggest that children transfer their prior learning to that of new words, with no
82 additional benefit of morphological relatedness. Given that this question has only been examined
83 in a single study to date, it seems important to continue exploration, especially with potentially
84 more sensitive metrics.

85 **The Current Study**

86 We investigated the effects of morphological structure on the processing and learning of
87 new words, as well as the transfer of that learning. We used a self-teaching task (e.g., Share,
88 1999), in which participants read short stories that included pseudowords while their eye
89 movements were recorded. As suggested by Bowey and Muller (2005) and de Jong and Share
90 (2007), orthographic learning occurs similarly regardless of whether stories are read aloud or
91 silently in a self-teaching paradigm. In the present study, we assumed an approach more typical
92 of the self-teaching literature than of the eye movement method; specifically, tracking oral

93 reading of stories allowed us to track decoding of the novel words and to ensure engagement in
94 the task. In a within-subjects manipulation, some of these were morphologically complex and
95 others were morphologically simple. Eye-tracking during this task supplied real-time information
96 about eye movements across exposures to the individual pseudowords as they were read
97 (Bertram, 2011). We used this data to explore our first question regarding the processing of new
98 words during reading. Subsequently, we used measures of learning to answer our second
99 research question, in which target items were included in a dictation task and an orthographic
100 choice task. To answer our final question of transfer, the orthographic choice task also included
101 items assessing transfer of learning to new pseudowords (e.g., Tucker et al., 2016). We again
102 measured eye movements in the orthographic choice task, in light of debate as to its sensitivity
103 (Tucker et al., 2016; Wang et al., 2011).

104 Our first research question investigated whether there was differential visual processing
105 during learning of morphologically versus orthographically complex pseudowords. Based on
106 prior studies of eye movements with new words (e.g., Joseph et al., 2014; Joseph & Nation 2018;
107 Li et al., 2019), we analysed classic eye-tracking measures, as they applied to the target
108 pseudowords. These included the Number of Fixations (NF) during the first-pass, the Gaze
109 Duration (GD) or the sum of the duration of fixations during the first-pass, and the Total
110 Duration (TD) or the sum of all fixation durations (first-pass and later passes). We also explored
111 fixation durations for both one (SFD for Single Fixation Duration) and two fixations (FTFD for
112 First-of-Two Fixation Duration and STFD for Second-of-Two Fixation Duration) (Mousikou &
113 Schroeder, 2019). Finally, we analyzed fixation positions to examine potential impacts of
114 morphological structure on gaze position during the repeated reading of the pseudowords; like
115 our analyses of fixation duration, these focused on gaze positions when one (SFP for Single

116 Fixation Position) or two fixations occurred (FTFP for First-of-Two Fixation Position and STFP
117 for Second-of-Two Fixation Position). This wide capture maximises insight offered by eye
118 movement measures into the real-time study of orthographic learning (Nation & Castles, 2017)
119 including potential differences between early (SFD, FTFD, GD, SFP, FTFP) and later processing
120 (NF, TD, STFD, STFP) (Bertram, 2011; see also Mousikou & Schroeder, 2019; Pagán & Nation,
121 2019). We expected an influence of morphological structure on early measures of visual
122 processing leading to earlier initial landing positions (SFP and FTFP) and longer gaze durations
123 (GD, SFD and FTFD) during the learning of morphologically versus orthographically complex
124 words. An inhibitory effect of morphological complexity was also expected on later measures of
125 eye movements (NF, TD, STFD and STFP), assuming that the presence of affixes might require
126 more high-level cognitive processes to assess the meaning of the pseudowords (Hyönä et al.,
127 2018). Finally, we expected to observe an easier visual processing of both types of pseudowords
128 leading to a decrease of all fixation durations across exposures.

129 Our second research question examined whether there was stronger learning for
130 morphologically than for orthographically complex pseudowords. No differences might emerge,
131 as in Tucker et al. (2016). However, we expected that our within-subjects design might enable
132 detection of stronger learning for morphologically than for orthographically complex
133 pseudowords, as predicted by Pacton et al. (2013; 2018). This could emerge in higher levels of
134 accuracy (and reduced visual processing time where measured) for morphologically versus
135 orthographically complex pseudowords during dictation and orthographic choice tasks.

136 Our final research question was whether English speaking adults transfer learning of
137 pseudowords to other pseudowords that are either morphologically or orthographically related. In
138 line with earlier work, we predicted that orthographic learning would transfer to the processing

139 of pseudowords that were morphologically related to a similar extent as those that were
140 orthographically related (Tucker et al., 2016). We expected similar levels of accuracy and
141 looking time durations on transfer items in the orthographic choice task.

142

143 **Method**

144 **Participants**

145 A total of 56 university students with normal or corrected-to-normal vision took part in this
146 study. We report data on 45 participants who met all criteria. Indeed, 3 out of the 56 participants
147 did not complete the whole experiment, 3 were not native English speaker, 1 had cognitive
148 difficulties, and 4 revealed word-level reading difficulties (i.e., word reading standard scores
149 < 85). Of the remaining participants, 37 were females, 8 were males, and the average age was
150 20.8 years (SD = 2.5 years). Furthermore, the average TOWRE score was 106.2 (SD = 12.8) for
151 Sight Word Efficiency and 103.7 (SD = 9.2) for Phonemic Decoding Efficiency.

152

153 **Apparatus**

154 We used the Eyelink 1000 eye tracker (SR Research; Mississauga, Ontario, Canada). Eye
155 movements were recorded from the right eye only at a sampling rate of 1000 Hz. Stimuli were
156 presented on a 1920×1200 px resolution Mac computer screen (60 Hz refresh rate) with
157 participants' eyes at a viewing distance of 81 cm. To keep this distance constant and prevent
158 head movement, participants rested their foreheads on a head mount. In all tasks, stimuli were
159 presented in black size 32 px Courier New font (which ensured equal distance between letters)
160 against a light grey background, and the experiments were designed with Opensesame (Mathôt et
161 al., 2012; v.3.1.2). The angular distance between letters was 0.37°.

162

163 **Materials**164 *Item Creation*

165 Pseudowords with 8 or 9 letters were created to fit into two conditions.

166 The morphological condition included morphologically complex pseudowords with 3
167 morphemes: a real prefix (either *re-* or *mis-*), a non-word base, and a real suffix (*-er*) (e.g.,
168 *releber* and *misdofer*). The orthographic condition had morphologically simple pseudowords
169 of the same length; for these, the letters added before the non-word base (either *pe-* or *fis-*) and
170 after (always *-le*) held no independent meaning in English (e.g., *pelerble* and *fisdoafle*). First
171 letters (*re-* vs *pe-*, *mis-* vs *fis-* and final letters (*-er* vs *-le*) were chosen based on prior research
172 with children (see Tucker et al., 2016). However, due to the increasing prevalence of
173 morphologically complex words in English with age, the frequency of prefixes *re-* or *mis-*
174 (respectively, $f = 27,867$ and $f = 3,495$ according to CELEX; Baayen et al., 1993) is higher than
175 the frequency of initial string as *pe-* or *fis-* (respectively, $f = 12,186$ and $f = 609$ according to the
176 CELEX) and the frequency of the suffix *-er* is higher than that of *-le* (respectively, $f = 58,043$
177 and $f = 35,756$ according to CELEX). All non-word bases and the complex pseudowords created
178 from them were confirmed to be pseudowords using CELEX and MCWord (Medler & Binder,
179 2005). We also confirmed that all pseudowords did not have real word homonyms or
180 orthographic neighbors (through dictionary.com). All pseudowords were constructed to be
181 orthographically legal in English, with initial and final trigram frequencies that were greater than
182 zero (according to CELEX) as well as whole word average bigram and trigram frequencies
183 greater than zero (according to MCWord).

184 To summarize, we created four lists of 16 pseudowords, each with eight morphologically
185 and eight orthographically complex pseudowords. The four lists were balanced for mean bigram
186 ($\beta = 0.02$, $t = 0.25$, $p = .803$) and trigram frequencies ($\beta = 0.11$, $t = 0.57$, $p = .574$).

187 Participants read the 16 pseudowords in a within-subject design so that each participant
188 learned items from both conditions. For example, one participant learned *releber* and *pejaitle*
189 and another learned *peleble* and *rejaieter*. We also created and counterbalanced homophones
190 across conditions such that half of the participants learned an item as a target, and the other half
191 learned its homophone twin (e.g., *relurber* and *releber*). Drawing on the above example, a third
192 participant would then learn *relurber* and *pejaytle* and a fourth would learn *pelurble* and *rejaieter*.
193 Each homophone pair was pronounceable following English grapheme–phoneme
194 correspondence rules (Rastle & Coltheart, 1999) and we also checked the regularity of the
195 pronunciation of each homophone pair of bases (Wilson, 1988; Ziegler et al., 1997). A full list of
196 items is provided as Supplementary Material¹ (see the “Appendix_Stimuli_lists” file).

197 ***Orthographic Learning Task***

198 To address our first question, we examined visual processing during story reading.
199 Participants read 16 stories out loud that included the pseudowords described above. Each story
200 consisted of five sentences, the last four of which each included one exposure to the pseudoword
201 (e.g., Mike has to go back outside during the storm and his hat gets wet. Mike decides to use the
202 *relurber* to fix his problem. The handy *relurber* will make his hat dry again. Mike is glad the
203 *relurber* can dry his hat. Mike makes sure to put the *relurber* away when he is finished). The first
204 sentence was used to establish the semantic context of the story and all subsequent sentences
205 were used to describe the use and function of the pseudoword. The sentences were presented one

¹ Open access availability for Supplementary Material files:
https://osf.io/jpbnz/?view_only=289450b9cf1f40efad6aec751b6b0a20

206 at a time, on a single horizontal line centered on the computer screen. Target pseudowords were
207 never at the beginning or at the end of the sentence. Across the morphological and orthographic
208 conditions, the sentences were matched on the number of words before the target so that the first
209 word and 5 letters after the target word were the same (see Hyönä et al., 2018 for a similar
210 approach). For the morphological condition, the meaning of the prefix and suffix in the
211 pseudoword was consistent with its use in English (e.g., pseudowords beginning in *re-* were
212 described as doing something again). During reading, the eye tracker recorded the participants'
213 eye movements; we also recorded their pronunciation. No feedback was provided on reading
214 accuracy.

215 *Dictation Task*

216 In the first outcome measure participants were asked to spell each of the pseudowords by
217 typing them on a computer. Participants heard the pseudowords one at a time, spoken aloud
218 through headphones. No feedback was provided during the task. Responses were considered
219 correct only if the whole spelling was strictly identical to that presented during the reading task.

220 *Orthographic Choice Task*

221 The second outcome measure was designed to measure both the outcome of learning and
222 its transfer (modeled on Tucker et al., 2016), addressing research questions 2 and 3. The task was
223 completed on a computer so that we could monitor eye movements. Participants were shown
224 four pseudowords arranged in a square around a fixation point on the screen (for a similar two by
225 two display of items, see Mimeau et al., 2018). They were asked to choose the best spelling,
226 based on what they had read in the stories. They were tested on the pseudowords they read as
227 well as transfer items for a total of 48 trials.

228 Within the orthographic choice task, the participants chose from four options: the learned
229 or transfer pseudoword, a homophone of that pseudoword, a distractor and a homophone of the
230 distractor (e.g., *relurber*, *releber*, *relurger*, *releger*). The first distractor was created by
231 replacing a consonant in the pseudoword base with another consonant (*relurger* for *relurber*).
232 The second distractor is the homophone of the first distractor (*releger* for *relurber*). No
233 feedback was provided during this task.

234 Transfer items were either morphologically or orthographically related to the learned
235 pseudowords. All transfer items shared the same non-word base as the pseudowords learned;
236 only the letters at the beginning were changed and the letters at the end were removed. For the
237 morphologically related pseudowords, the suffix was replaced with another real word suffix; the
238 letters *re-* and *mis-* were changed to *mis-* and *re-*, respectively. Similarly, for the orthographically
239 related pseudowords, the letters *pe-* and *fis-* were changed to *fis-* and *pe-*, respectively. For each
240 pseudoword, the two last letters were removed. As an example, for the target pseudoword
241 *relurber* we used *mislurb* to test morphological transfer and *fislurb* to test orthographic transfer.

242 ***Test Of Word Reading Efficiency (TOWRE-2)***

243 Lastly, participants completed the TOWRE-2 (Torgesen et al., 2012) to assess reading
244 level. In each subtest, participants were asked to read as many real words or pseudowords as they
245 could in 45 seconds.

246

247 **Procedure**

248 All testing was completed during a single session in a quiet testing room. Participants
249 completed tasks in the order above. Prior to each eye-tracking task, we conducted a 5-point
250 calibration. During the orthographic learning task, stories were presented in a random order and

251 preceded by a manual drift correction dot centered on the screen. To avoid any anarchical initial
252 gaze position, each sentence was preceded by a fixation cross indicating the position of the first
253 letter of the sentence. The participant had to keep their eyes on this cross between 150 to 250 ms
254 to display the whole sentence, allowing recalibration if necessary.

255 In the orthographic choice task, each trial was preceded by a fixation dot centered on the
256 screen serving as a drift correction. After manual validation, the four stimuli appeared. Position
257 of the target items was counterbalanced, with target pseudowords randomly appearing 12 times
258 in each corner of the square.

259 For each of these tasks as well as for the dictation task, participants pressed the space bar
260 to move onto the next trial so that there was no time limit imposed. In each task, test trials were
261 preceded by at least 2 practice trials to ensure understanding of the instructions.

262

263 **Results**

264 **Statistical Models**

265 Raw data from all tasks were analyzed by means of generalized linear mixed effects
266 models (glmer function; R Core Team, 2018; RStudio version 1.0.143). In all statistical models,
267 participants and items were introduced as random factors and initial bigram (for items beginning
268 by *re-* or *pe-*) or trigram (for items beginning by *mis-* or *fis-*) log-frequency was included as
269 covariate. As an exception, word length was also considered as covariate for the analysis of the
270 nature effect (new vs. old items) on gaze duration from the orthographic choice task. This was
271 done assuming a potential word length effect on visual processing due to the large range of word
272 lengths (from 6 to 9 letters) of items compared through this model.

273 We used the Gamma family and the identity link for reaction time (RT) data (including
274 temporal measures from eye-tracking data), the Poisson family and the identity link for the
275 analysis of the number of fixations, the Gaussian family and the identity link for the analysis of
276 fixation positions, and the Binomial family and the logit link for binomial variables such as
277 accuracy. In all models, contrasts were specified as 0.5/-0.5 or 1.5/0.5/-0.5/-1.5 respectively for
278 independent variables which have 2 or 4 modalities.

279 Models from the orthographic learning task included the within-subjects variables of
280 number of exposures (1, 2, 3, 4) and item type (morphologically vs. orthographically complex)
281 as well as their interaction as fixed factors. Models from the dictation task included item type
282 (morphologically vs. orthographically complex) as a fixed factor. In models related to the
283 orthographic choice task, three independent fixed factors were considered in 3 different models:
284 the within-subjects variable of item type (morphologically vs. orthographically complex),
285 transfer type (morphologically vs. orthographically related) and nature (new vs. old items).

286 Finally, a maximal random effects structure was first specified for all models including all
287 subject and item random intercepts and random slopes (Barr et al., 2013). Following Barr et al.
288 (2013) recommendations and in the case of a model failing to converge, we removed first
289 correlations between random factors, then random interactions, and lastly random slopes
290 associated with smaller variance, until the model converged. Full model details and results are
291 provided as Supplementary Material² (for a quick access to statistical models, see the .html file
292 in “Statistical_files” folder).

293

294 **Eye-Tracking Data Cleaning**

² Open access availability for Supplementary Material files:
https://osf.io/jpbnz/?view_only=289450b9cf1f40efad6aec751b6b0a20

295 Raw data were parsed using the Eyelink cognitive configuration. We used a custom-
296 designed software developed from the technical computing system Mathematica (Wolfram
297 Research Inc., Champaign, Illinois, United States; v.11.0) to select the relevant fixations for
298 subsequent analyses. For both the orthographic learning and orthographic choice tasks, only
299 events that occurred within the area of interest (i.e., area around the target word) were analyzed³.

300 For both the learning and orthographic choice tasks, we inspected and removed possible
301 outliers⁴. First, trials containing more than one blink in the area of interest were removed. Then,
302 trials with more than 6 fixations for the orthographic learning task and trials with more than 14
303 fixations for the orthographic choice task were considered as extreme outliers according to the
304 interquartile range calculation $Q_3 + 3 \times (Q_3 - Q_1)$. Trials with total log-duration further than 2.5
305 standard-deviations from the mean were removed (range: 105 – 3,075 ms for the orthographic
306 learning task; range: 163 – 4,125ms for the orthographic choice task). Fifth, we excluded trials
307 with at least one fixation log-duration further than 2.5 standard-deviations from the mean (range:
308 67 – 792 ms for the orthographic learning task; range: 58 – 789 ms for the orthographic choice
309 task). In total, we retained 90.9 % of trials (2,618 out of 2,880 trials⁵) from 45 participants and
310 89.2 % of trials (1,883 out of 2,112 trials) from 44 participants (due to technical issue, data from
311 one participant were not recorded) for analysis.

312

³ These areas were defined as 0.57° to the left of the left boundary of the first letter, 0.57° to the right of the right boundary of the final letter and consistent vertical coordinate according to visual inspection carried out for each participant, for the orthographic learning task; 0.57° to the left of the left boundary of the first letter, 0.57° to the right of the right boundary of the final letter and more or less 3° from the center of the target word on the vertical axis, for the orthographic choice task.

⁴ For the orthographic choice task, outliers were removed for the analysis of gaze duration but not for the analysis of accuracy.

⁵ A complete breakdown of the number of trials considered as a function of item type and number of exposures is provided in Supplementary Material file “Complement for Eye-Tracking data”. See: https://osf.io/jpbnz/?view_only=289450b9cf1f40efad6aec751b6b0a20.

313 **Data Analyses**314 *Differences in the Processing During the Learning of Morphologically and Orthographically*315 *Complex Pseudowords*

316 To address our first research question, eye movements were recorded during the
317 orthographic learning task itself allowing us to compare visual processing of morphologically
318 and orthographically complex pseudowords during repeated reading. While most previous
319 studies in the field focused on the duration of both single fixation and first-of-multiple fixations
320 (e.g., Joseph et al., 2014), we restricted analyses of fixation duration and position to trials in
321 which the target pseudoword was fixated upon once or twice (Mousikou & Schroeder, 2019).
322 This proposal is doubly motivated; eye movement data from the orthographic learning task
323 revealed that 58 % of trials required one (24.6 %) or two (33.3 %) fixations, and analysis of first-
324 of-multiple fixations duration⁶ revealed similar effects to those obtained analysing the first-of-
325 two fixation duration. Thus, the analysis of two-fixation trials allowed an in-depth analysis of
326 both the first and second fixation duration, while capturing patterns similar across more
327 fixations, thereby allowing us to provide insights related to our first research question.

328 The number of exposures and item type did have an effect on visual processing times – and
329 consequently, the number of fixations –for the pseudowords (see Figure 1). Namely, NF, GD,
330 TD, FTFD and STFD significantly decreased across exposures (respectively, $\beta = 0.41, z = 15.05$;
331 $\beta = 124.73, t = 26.90$; $\beta = 197.45, t = 43.82$; $\beta = 21.55, t = 6.50$ and $\beta = 12.11, t = 3.68$, all $p_s <$
332 $.001$), but SFD was not influenced by the number of exposures ($\beta = 3.91, t = 1.15, p = .250$).

⁶ The analysis of first-of-multiple fixation duration showed a main effect of the number of exposures ($\beta = 11.44, t = 6.02, p < .001$) but neither a main effect of item type ($\beta = 4.85, t = 0.78, p = .438$) nor interaction effect ($\beta = -0.88, t = -0.24, p = .810$).

333 There were significantly more fixations for orthographically complex than morphologically
334 complex pseudowords ($\beta = 0.17, z = 2.72, p = .006$). In line with this observation, there were
335 also longer processing times for orthographically complex pseudowords over morphologically
336 complex one (GD: $\beta = 40.45, t = 4.52, p < .001$ and TD: $\beta = 31.10, t = 4.14, p < .001$). In
337 contrast, results did not show any significant effect of item type for SFD, FTFD and STFD
338 (respectively, $\beta = -4.03, t = -0.39, p = .697$; $\beta = 7.47, t = 0.85, p = .393$; $\beta = 12.43, t = 1.25, p =$
339 $.210$) suggesting that the presence – or the absence – of morphemes in a new word does not
340 appear to influence fixation durations, in contrast to its effect on visual processing as a whole (as
341 measured by NF, GD and TD).

342 The absence of an item-type \times exposures interaction for NF and FTFD suggests that
343 processing times decreased similarly for both types of pseudowords across exposures
344 (respectively, $\beta = 0.04, z = 0.80, p = .424$; $\beta = -3.27, t = -0.51, p = .612$). Nevertheless, there was
345 an interaction effect for GD, TD and STFD (respectively, $\beta = 29.37, t = 4.27, p < .001$; $\beta =$
346 $23.28, t = 3.82, p < .001$; $\beta = 20.52, t = 3.24, p = .001$) and a trend towards one for SFD ($\beta = -$
347 $11.83, t = -1.81, p = .071$). This suggests that there were eye movement variations across
348 exposures depending on item type. Indeed, there were faster decreases in GD, TD and STFD for
349 orthographically complex than for morphologically complex pseudowords, and SFD tended to be
350 higher for orthographically complex than for morphologically complex pseudowords between
351 the three first exposures and the final exposure. Finally, FTFD did not depend on initial bi- or
352 trigram log-frequency ($\beta = -2.13, t = -1.04, p = .298$). However, the higher the latter, the lower
353 the GD, TD and STFD (respectively, $\beta = -11.80, t = -5.29, p < .001$; $\beta = -15.97, t = -5.74, p <$
354 $.001$; $\beta = -5.34, t = -2.45, p = .014$). These results suggest that frequency of the beginning of the

355 pseudoword impacted visual processing. In contrast, results showed longer SFD for higher
356 initial bi- or trigram log-frequency ($\beta = 5.58, t = 2.06, p = .039$).

357 Finally, results related to gaze position are presented Table 1. In contrast with processing
358 times, we observed a main effect of the number of exposures only on SFP ($\beta = -0.31, t = -4.48, p$
359 $< .001$; FTFP: $\beta = 0.05, t = 0.97, p = .333$; STFP: $\beta = -0.12, t = -1.60, p = .114$). These show that
360 gaze position shifts to the right of the target pseudowords across exposures, with a similar shift
361 when this is the first or second of two fixations. There was no main effects of item type on gaze
362 position (SFP: $\beta = -0.19, t = -1.09, p = .276$, FTFP: $\beta = -0.11, t = -0.87, p = .383$ and STFP: $\beta = -$
363 $0.19, t = -1.14, p = .257$) suggesting that there were no differences in location of fixations for
364 morphologically complex and orthographically complex pseudowords. Interestingly, across
365 exposures for trials with two fixations, there was a trend towards an item-type \times exposures
366 interaction effect (FTFP: $\beta = -0.21, t = -1.95, p = .051$); this showed that first fixation position
367 tends to shift to the left of the string between the second and third exposure during the processing
368 of morphologically complex pseudowords, while it systematically shifted to the right of the
369 string during the processing of orthographically complex pseudowords. No interaction effect was
370 found neither for SFP nor for STFP (respectively, $\beta = -0.13, t = -0.95, p = .343$ and $\beta = 0.10, t =$
371 $0.65, p = .516$). Finally, the effect of initial bi- or trigram log-frequency effect was not significant
372 (all $p_s > .250$), except for SFTP ($\beta = -0.25, t = -4.45, p < .001$), suggesting that landing position
373 was not influenced by this variable.

374 Together these results suggest that there is differential visual processing during learning;
375 morphological complexity facilitates the processing of pseudowords, reflected by shorter visual
376 processing times (i.e., GD, TD and consequently, NF) for the whole pseudoword during the early
377 stages of orthographic learning. This facilitatory effect disappears over exposures, with some

378 evidence that, after only a few encounters with a pseudoword, the presence of morphemes
379 appears to not only guide gaze position, but also leads to an increase in processing time.

380 *Stronger Learning of Morphologically and Orthographically Complex Pseudowords*

381 Results from both the dictation and orthographic choice tasks addressed our second
382 research question as to whether there are differences in the strength of learning of
383 morphologically and orthographically complex pseudowords. For the dictation task,
384 morphologically complex pseudowords were spelled more accurately than orthographically
385 complex pseudowords ($\beta = -0.64$, $z = -2.13$, $p = .033$; 40.6% and 26.4%, respectively), with no
386 main effect of initial bi- or trigram log-frequency ($\beta = 0.09$, $z = 0.83$, $p = .407$). These results
387 suggest that morphological structure facilitates the learning of precise orthographic
388 representations of pseudowords, independently of their initial word frequency.

389 In the orthographic choice task, linear models (lm function) first showed that participants
390 performed above chance (25 %) for target orthographically and morphologically complex
391 pseudowords that they read in stories (respectively, $\beta = 42.33$, $t = 14.02$ and $\beta = 48.58$, $t = 16.39$,
392 $p_s < .001$). As further evidence of learning, orthographically and morphologically complex
393 pseudowords read during the orthographic learning task were recognized more accurately than
394 new pseudowords testing transfer ($\beta = 0.78$, $z = 5.37$, $p < .001$) and required longer visual
395 processing time ($\beta = 108.97$, $t = 5.93$, $p < .001$). Comparing results related to orthographically
396 and morphologically complex pseudowords learned through stories, results revealed that
397 accuracy did not depend on item type ($\beta = -0.36$, $z = -1.34$, $p = .180$). Further, in line with results
398 from the dictation task, there was no main effect of initial bi- or trigram log-frequency on gaze
399 duration ($\beta = 2.37$, $t = 0.33$, $p = .744$) nor accuracy ($\beta = -0.01$, $z = -0.12$, $p = .903$). Interestingly,
400 eye movement data (see Table 2) provided additional insight. There was a significant main effect

401 of item type on TD, that is, times were longer for orthographically complex than for
402 morphologically complex pseudowords ($\beta = 75.4, t = 2.85, p = .004$).

403 Together these results suggest stronger learning of morphologically than orthographically
404 complex pseudowords, with greater accuracy in spelling of morphologically than
405 orthographically complex pseudowords, when testing on a dictation task. Morphologically
406 complex pseudowords also require less visual processing to be recognized accurately, although
407 there were no differences in accuracy on this task.

408 *Transfer of Learning*

409 Our final research question was whether participants transfer their learning of pseudowords
410 to facilitate the processing of other pseudowords, that are either morphologically or
411 orthographically related. To answer this question, we analyzed accuracy and gaze duration data
412 for the orthographic choice task. We focused on performance in the conditions testing processing
413 of pseudowords that were either morphologically (MT) or orthographically (OT) related to
414 pseudowords read during the orthographic learning task. Table 2 summarizes accuracy and total
415 gaze duration on target items from the orthographic choice task (see columns 3 and 4 for MT and
416 OT results). Statistical analyses of total gaze duration were conducted on correct responses only,
417 leading to us consider 1142 out of 2112 trials in our analysis.

418 Linear models (lm function) showed that participants performed above chance (25 %) for
419 OT and MT items (respectively, $\beta = 29.55, t = 11.98$ and $\beta = 29.97, t = 11.39, p_s < .001$),
420 pointing to the fact that readers did transfer their learning. Beyond this, we tested whether the
421 extent of transfer to new pseudowords differed on the presence of morphological structure. We
422 did not detect a statistical difference in accuracy between OT and MT items ($\beta = -0.02, z = -0.17,$
423 $p = .868$), nor a difference in total gaze duration (i.e., the sum of all fixation durations that

424 occurred on the target pseudowords; $\beta = -2.05$, $t = -0.10$, $p = .923$). There was also no effect of
425 initial bi- or trigram log-frequency on total gaze duration ($\beta = -3.34$, $t = -0.44$, $p = .660$). These
426 findings suggest that transfer occurs, yet to a similar extent for the identification of accurate
427 spellings of morphologically and orthographically complex words including similar processing
428 times.

429

430

Discussion

431 In the present study, we examined adults' processing, learning and transfer of learning of
432 morphologically and orthographically complex pseudowords that they read aloud in short stories.
433 This work extends earlier studies by focusing on complex words, shifting from the traditional
434 dominance of simple words in the orthographic learning literature, as well as in integrating eye-
435 movement methods. In our study, adult English-speakers read short stories containing four
436 instances of 16 morphologically or orthographically complex pseudowords, followed by
437 outcome measures of dictation and orthographic choice tasks. This design enabled us to explore
438 differential processing and/or learning of morphologically versus orthographically complex
439 pseudowords. We also evaluated whether morphological structure influenced the degree to which
440 English speaking adults transfer their learning of pseudowords.

441 Our first question was whether there was an effect of morphological structure on
442 participants' visual processing of pseudowords that they read repeatedly in texts. A first set of
443 findings revealed that participants required more fixations and longer processing times – in both
444 gaze duration and total duration – to process orthographically over morphologically complex
445 pseudowords, suggesting that morphological structure might facilitate information gathering of
446 the letters that compose a new word. These observations contrast with prior evidence of longer

447 processing times for polymorphemic rather than for monomorphemic known words (Hyönä et
448 al., 2018). Notably, this discrepancy could result from differences in the processing of unknown
449 versus known words. In our study, we observed a faster decrease for orthographically over
450 morphologically complex pseudowords in gaze duration and single fixation duration, reflecting
451 early processing (Pagán & Nation, 2019), and also in total duration and second-of-two fixation
452 duration which is associated with later processing (Mousikou & Schroeder, 2019). As such, our
453 results suggest that during the very first stages of orthographic learning, both early and later
454 visual processing times decrease as a function of morphological complexity, while the presence
455 of suffixes increases processing difficulty after few encounters. Polymorphemic pseudowords
456 involving the processing of semantic clues, recruiting higher-level cognitive processes (Hyönä et
457 al., 2018) and, likely only taking place once efficient orthographic representations are established
458 in memory. Thus, further studies examining the transition in lexical status, from unknown to
459 known words, are important.

460 Another set of findings are more tentative but allude to additional differences in processing
461 based on morphological structure. When one fixation occurred, gaze position shifted to the right
462 across exposures for both word types. However, when two fixations occurred, gaze positions
463 shifted differently across exposures for morphologically and orthographically complex
464 pseudowords. The first-of-two fixation position shifted to the beginning of morphologically
465 complex pseudowords (in our case, closer to the prefix), whereas it gets closer to the optimal
466 viewing position of the orthographically complex pseudowords (O'Regan & Jacobs, 1992). The
467 second-of-two fixation position shifted to the end of the string regardless of word type. Like
468 Hyönä et al. (2018), we argue that our results demonstrate “an effect of high-level cognitive
469 processes on saccade-target selection during reading” (p. 126). Interestingly, this aligns with our

470 observation of increases in later visual processing times (i.e., STFD) across exposures. Thus,
471 with enhanced orthographic representation, eye movements are increasingly guided by
472 morphological structure.

473 Second, we found several points of evidence for stronger learning of the spellings of
474 pseudowords read in story contexts when these were morphologically complex pseudowords
475 than when they were not. Morphologically complex pseudowords were more accurately spelled
476 than orthographically complex pseudowords, and required less time for visual processing in the
477 orthographic choice task. These findings support robust observations that polymorphemic real
478 words are more accurately spelled (e.g., Deacon & Dhooge, 2010) and are read more quickly and
479 accurately (e.g., Deacon et al., 2010) than control words. They also align with some prior studies
480 of eye-tracking in pseudowords, albeit not in an orthographic learning paradigm (Breadmore &
481 Carroll, 2018). Here we extend this pattern to the learning of new pseudowords orthographic
482 representations, also building on Tucker et al. (2016). Notably, accuracy scores from the
483 orthographic choice task revealed no additional effect of morphological structure on
484 orthographic learning. These findings are consistent with Tucker et al. (2016) and point to a
485 potential lack of sensitivity in this task. Overall, participants were better able to learn to spell and
486 were quicker to accurately recognise morphologically over orthographically complex
487 pseudowords, suggesting that the presence of morphological structure in new words facilitates
488 learning of their orthographic form.

489 Finally, we found that adults transfer their learning of pseudowords to that of other
490 pseudowords, contrasting with the strict item-by-item predictions of the self-teaching hypothesis
491 (Share, 1999). Adults performed above chance in the orthographic choice task for the items
492 testing across both morphological and orthographic complexity. These findings suggest that

493 orthographic learning is indeed transferred to new words. However, there were no differences
494 based on morphological structure in the extent of learning transfer, as measured by accuracy or
495 visual processing time observed in orthographic choice. Overall, in keeping with findings from
496 Tucker et al. (2016), visual recognition of new pseudowords – reflecting the ability to transfer
497 learning – might not be influenced by their morphological relatedness to learned pseudowords.
498 That said, we did identify effects of morphological structure during the learning process, in
499 keeping with Pacton et al. (2018). As such the presence of morphologically complex words
500 during the learning process itself might strengthen learning with little influence of such structure
501 on later transfer of learning. Further research should continue to evaluate separately the influence
502 of morphological structure on the learning of morphologically complex words versus the transfer
503 of that learning.

504 This distinction brings forward an important theoretical implication of our research. The
505 distinction between the role of morphological structure in the learning of new words versus the
506 transfer of that learning is not made in the Self-Teaching Hypothesis, the dominant theory of the
507 process of orthographic learning to date. We agree with Tamura et al. (2017) regarding the need
508 to examine both the acquisition of new words into the lexicon and subsequent engagement with
509 those words. In our view, the effect of morphological structure might depend crucially on
510 multiple experiences with words, which enable the accumulation of information about the
511 orthographic structure and the meaning of them, both features central to morphological
512 processing. As such, experience with words may give rise to an effect of morphological
513 structure, and research attending to this experience is likely to more clearly elucidate connections
514 between orthographic learning and the establishment of one's lexicon.

515 There are several limitations to our work. Our evidence of shorter visual processing times
516 for morphologically complex over orthographically complex (but morphologically simple)
517 pseudowords during the orthographic choice task differs from previous studies on real word
518 processing in sentences. These studies found that gaze duration and first fixation duration
519 increase as a function of morphological complexity (e.g., Hyönä et al., 2018; Inhoff et al., 1996).
520 Contrasting patterns could be due to differences between lexical processing of known and
521 unknown words (e.g., Tamura et al., 2017) or in tasks (Wang et al., 2011). For instance, the
522 dictation task was sensitive to the effects of morphological structure, but there was also quite low
523 accuracy for this task suggesting that more exposures might be needed to learn the orthographic
524 form of long words. Further, effects sometimes diverged in classic behavioural measures and
525 eye-tracking metrics; the latter offered insight into differential visual processing both in outcome
526 metrics and in the process of learning. We also note that our results from the orthographic choice
527 measure point to the need to move beyond this task, even if it is simply towards monitoring
528 looking time within it. On the topic of tasks, future studies could include morphological
529 decoding and awareness (e.g., Deacon et al., 2017), given evidence of individual differences in
530 these (for review see Deacon et al., 2019) that might be relevant to understanding. Finally, in the
531 present study, we focused on first-of-two fixation instead of first-of-multiple fixation (e.g.,
532 Joseph et al., 2014). While this limited the analyses to a subsample, results suggested that trials
533 which required exactly two fixations are representative of trials which required two or more
534 fixations. As such, we think that our results are representative beyond this set, while also offering
535 more precise insights into shifts in eye movement during processing.

536 In summary, we combined a classic self-teaching paradigm with eye-tracking technology
537 to examine adults' processing, learning and transfer of that learning of morphologically and

538 orthographically complex pseudowords. Eye movement behavior examined on an exposure-by-
539 exposure basis revealed subtle and clear differences in eye movements based on the presence of
540 morphological structure. Further, measures of eye movements, combined with behavioral results,
541 suggest stronger learning of morphologically over orthographically complex pseudowords after
542 just four encounters. Finally, we found clear evidence of transfer of learning to other
543 pseudowords, to a similar extent for both orthographically and morphologically related
544 pseudowords. Our findings open new theoretical and methodological perspectives in the study of
545 cognitive processes implied in orthographic learning and the transfer of that learning.

546

547

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Conflict of interest statement

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

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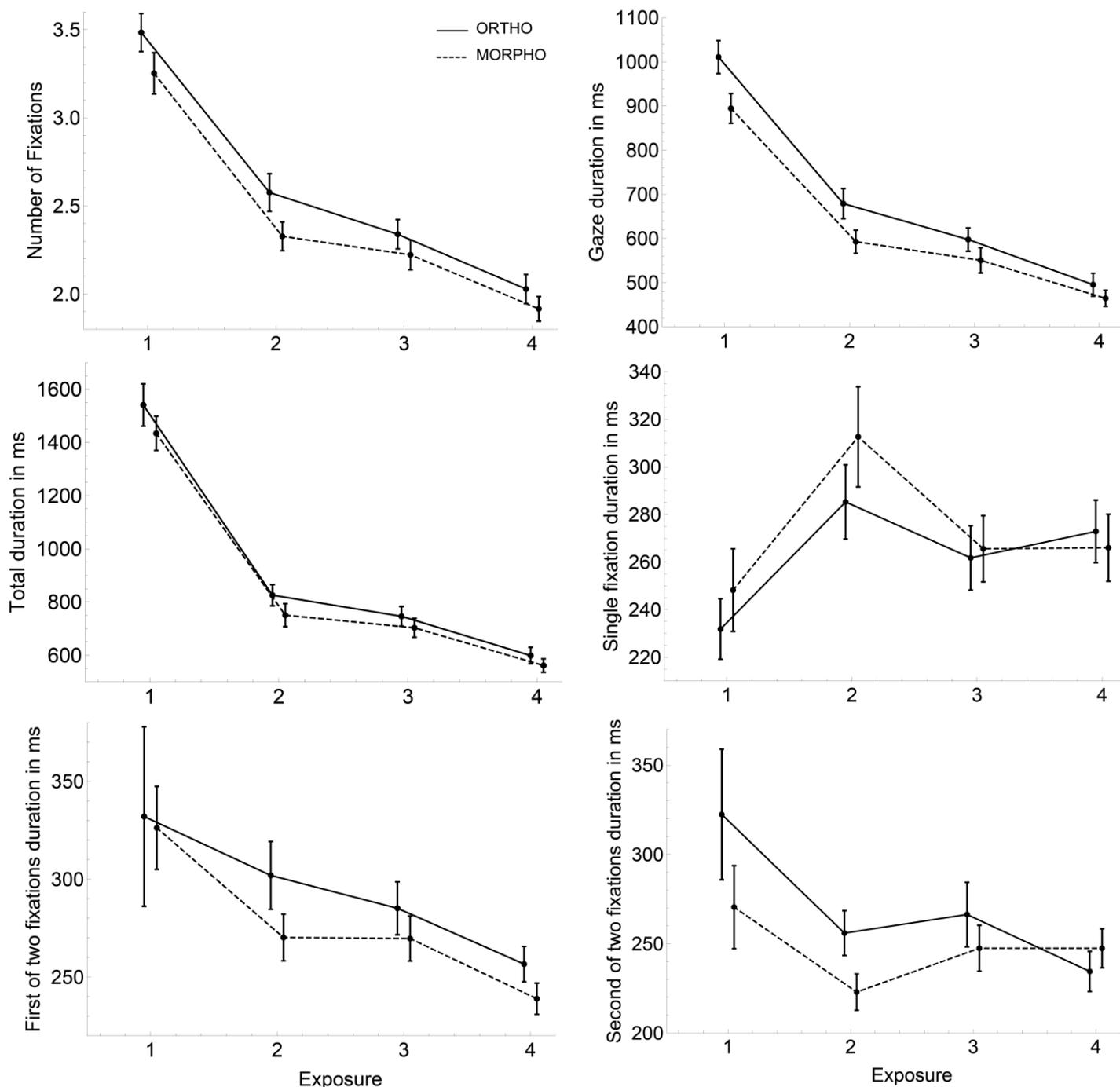


Figure 1

Eye movement measures recorded during the orthographic learning task as a function of the number of exposures. Are represented, from top to bottom and from left to right: Number of Fixation (NF), Gaze Duration (GD), Total Duration (TD), Single Fixation Duration (SFD), First-of-Two Fixation Duration (FTFD) and Second-of-Two Fixation Duration (STFD). All times are in ms and vertical bars are for standard errors.

Table 1

Mean (and Standard Deviations) for Eye Movement Data from the Orthographic Learning Task as a Function of Item Type and Number of Exposures

Item type	O				M			
	Exposure 1	2	3	4	1	2	3	4
SFP	2.12 (1.29)	2.60 (1.27)	2.85 (1.53)	3.31 (1.79)	2.43 (1.47)	2.84 (1.39)	2.85 (1.35)	3.27 (1.04)
FTFP	2.10 (1.27)	2.41 (1.09)	2.43 (1.21)	2.56 (1.31)	2.54 (1.11)	2.80 (1.23)	2.36 (1.17)	2.27 (1.09)
STFP	4.49 (2.06)	5.41 (1.69)	5.40 (1.35)	5.45 (1.31)	4.47 (1.80)	5.15 (1.60)	5.37 (1.33)	5.33 (1.23)

Note. O: orthographically complex; M: morphologically complex Gaze positions (SFP: Single Fixation Position; FTFP: First-of-Two Fixation Position; STFP: Second-of-Two Fixation Position) correspond to the position of the fixated letter in the string (continuous value).

Table 2

Accuracy and Total Duration Obtained in the Orthographic Choice Task as a Function of Item Type

	O	M	OT	MT
Accuracy (SD) in %	67.3 (20.0)	73.6 (19.7)	54.5 (16.4)	55.0 (17.4)
Total Duration (SD) in ms	1,041 (375)	977 (325)	1,093 (512)	1,045 (393)

Note. O: orthographically complex; M: morphologically complex; OT: orthographically related; MT: morphologically related. Standard deviations are specified in brackets.