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# Does the Relation between Rapid Automatized Naming and Reading Depend on Age or on Reading Level? A Behavioral and ERP Study

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1           **Does the relation between Rapid Automatized Naming and**  
2           **reading depend on age or on reading level?**  
3           **A behavioral and ERP study**

4  
5           Marjolaine Cohen <sup>1,\*</sup>, Gwendoline Mahé <sup>1,2</sup>, Marina Laganaro <sup>1</sup> and Pascal Zesiger <sup>1</sup>  
6

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49 Abstract

50

51 Reading predictors evolve through age: phonological awareness is the best predictor of  
52 reading abilities at the beginning of reading acquisition while Rapid Automatized Naming  
53 (RAN) becomes the best reading predictor in more experienced readers (around 9-10  
54 years old). Those developmental changes in the relationship between RAN and reading have  
55 so far been explained in term of participants' age. However, it should be noted that in the  
56 previous experiments age always co-vary with participants reading level. It is thus not clear  
57 whether RAN-reading relationship is developmental in nature or related to the reading system  
58 itself. This study investigates whether the behavioral changes in the relationship between RAN  
59 and reading and their electrophysiological correlates are related to the chronological age or to  
60 the reading level of the participants. 32 French-speaking children aged 7 to 10 years took part  
61 to the experiment: they were divided into groups contrasted on age but with similar reading  
62 levels and the other way round. Participants performed two reading tasks and four RAN tasks.  
63 EEG/ERP was recorded during discrete letter and picture RAN. Behavioral results revealed that  
64 alphanumeric RAN is more sensitive to age variations than reading level differences. The  
65 inverse profile was revealed for picture RAN, which discriminate poor and good readers among  
66 typically developed children within the same age-group. ERPs of both letter and picture RAN  
67 differed across age groups whereas only for the picture RAN ERPs differed across reading  
68 levels. Taken together, these results suggest that picture RAN is a particularly good indicator  
69 of reading level variance independently of age.

70

71 **Keywords: reading/rapid automatized naming/ERP/children/French**

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## 76 1. Introduction

77

78 Literacy skills are an essential asset in our modern societies as they are critical for academic  
79 and professional achievement as well as for social integration. Five years of academic training  
80 in a specific orthographic system are necessary to reach an expert reading level (Aghababian &  
81 Nazir, 2000), characterized by effortless, rapid and accurate reading. Despite the special focus  
82 placed on reading acquisition over the first school grades, there are huge inter-individual  
83 differences in the ease and speed children display in learning to read. Variability in reading  
84 skills has been reliably associated with performance in non-reading tasks, and in particular with  
85 rapid automatized naming (RAN) tasks. RAN, defined as the ability to name quickly and  
86 accurately items displayed on a grid, is a strong predictor of reading skills once children have  
87 achieved a certain level of proficiency, usually after the age of nine years or after Grade 3 (de  
88 Jong, 2011; van den Bos, Zijlstra, Iutje Spelberg, 2009). It is however not clear whether the  
89 onset of the close RAN-reading relationship is dependent on the degree of expertise in reading,  
90 or on the chronological age of the participants, as both variables usually co-vary. The present  
91 study aims at investigating whether the RAN-reading relationship is more closely related to the  
92 chronological age of the participants, or to their degree of expertise in literacy. An additional  
93 insight in the relation between RAN and reading is achieved through the EEG/ERP recording  
94 during the RAN tasks, allowing investigating whether the neurophysiological changes due to  
95 age and to reading level are the same.

96

97 From the 1970s, a wealth of scientific studies has been dedicated to understanding the processes  
98 and determinants involved in learning to read, resulting in several consensual statements that  
99 we summarize below. First, reading involves both specific written word identification skills,  
100 and more general text comprehension skills (Hoover & Gough, 1990). In order to identify  
101 written words, the reader is thought to develop two pathways (Coltheart, Curtis, Atkins, &  
102 Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). The indirect, non-lexical  
103 pathway consists in grapheme-to-phoneme mappings and thus allows reading of consistent  
104 words and pseudowords. At the beginning of learning to read, the non-lexical route is the only  
105 one available for children (Ehri, 2014). With reading instruction and practice, the repeated  
106 decoding of the same words leads to the development of the lexical pathway, in which whole-  
107 word orthographic representations are stored. This route enables the reader to correctly and  
108 rapidly identify familiar words, whether they are consistent or not. It is the most frequently used  
109 route in expert readers (Ehri, 2014). At the first stages of reading acquisition, reading relies  
110 heavily on grapheme-to-phoneme mapping, phonological awareness (PA) is thus an excellent  
111 predictor of reading skills in early grades. With reading practice, reading relies more and more  
112 on the lexical route, whose efficiency is based on rapid access to phonological information from  
113 orthographic shapes. This cognitive process is thought to be highly similar to the processing  
114 stages taking place during a RAN task. Thus RAN appeared to be a better predictor of reading  
115 outcomes in older children (Parrila, Kirby & McQuarrie, 2004). The dual-route approach has  
116 recently provided a comprehensive account of the factors that affect reading aloud (e.g.,  
117 frequency, length, consistency and lexicality effects) in both skilled and reading disabled  
118 children (Perry, Ziegler, & Zorzi, 2007; Perry, Ziegler, Braun, & Zorzi, 2010). Second, there  
119 are large inter-individual differences in word identification skills. Most studies involving  
120 typically developing children report a Gaussian distribution of reading skills (Plaza & Cohen,  
121 2005; see Kirby, Georgiou, Martinussen, & Parrila, 2010 for a review). Some authors however  
122 suggested that different groups of poor readers can be distinguished among typically developing  
123 learners on the basis of their level of performance in reading (i.e. -2 vs. -1 standard deviation  
124 from the mean) and/or of associated features (i.e. poor readers showing a single PA or RAN  
125 deficit vs. those with a deficit in both PA and RAN) (Cronin, 2013; deGroot, van den Bos,

126 Minaret, & van der Meulen, 2015). In fact, considerable inter-individual differences have been  
127 reported in skills associated with reading, such as PA, phonological short-term memory  
128 (PSTM) and RAN (Caravolas, Hulme, & Snowling, 2001; Gathercole et Baddeley, 1993; Kirby  
129 et al. 2010; Mann, Cowin, & Schoenheimer, 1989). Here we will focus on RAN tasks, as their  
130 relation with reading skills still raises a number of issues.

131  
132 Performance at RAN tasks is a reliable predictor of both concurrent and later literacy skills in  
133 children (and in adults) (i.e. Kirby et al. 2010; Georgiou, Papadopoulos, Fella, & Parrila, 2012;  
134 Georgiou, Parrila, Cui, & Papadopoulos, 2013; Georgiou, Aro, Liao, & Parrila, 2016). The  
135 strength of the RAN-reading relationship is modulated by several factors related to the  
136 characteristics of tasks used to assess RAN and reading. For example, regarding the RAN task  
137 itself, the predictive power of serial RAN on reading fluency is stronger than that of discrete  
138 RAN (Georgiou et al., 2013; Logan, Schatschneider, & Wagner, 2011). However, recent  
139 findings suggest that discrete RAN (i.e., with items displayed one by one on a computer screen)  
140 may be an indicator of efficient reading by sight strategy (deJong, 2011; Protopapas, Altani, &  
141 Georgiou, 2013). Furthermore, the RAN task can be composed of letters, digits, pictures or  
142 colors. In most studies, the children's performance in RAN tests using alphanumeric items has  
143 been demonstrated to be a stronger predictor of literacy skills than performance in RAN tests  
144 using pictures and colors (i.e. Savage, Pillay, & Melidona, 2008; Schatschneider, Fletcher,  
145 Francis, Carlson, & Foorman, 2004). However, significant correlations between picture/color  
146 RAN tasks performance and literacy skills have also been reported (i.e. Albuquerque, 2012;  
147 Caravolas, Lervåg, Mousikou, Efrim, Litavský, Onochie-Quintanilla et al., 2012; Pauly,  
148 Linkersdörfer, Lindberg, Woerner, Hasselhorn, & Lonnemann, 2011), and in some studies,  
149 picture RAN appeared to be more predictive than alphanumeric RAN (i.e. Arnell, Joanisse,  
150 Klein, Busseri, & Tannock, 2009). Regarding the reading measure, RAN has been reported to  
151 be a particularly strong predictor of reading fluency (Rakhlin, Cardoso-Martins, & Grigorenko,  
152 2014). Moreover, the relation between RAN and reading is not only dependent on the tasks  
153 properties, but also on variables related to the characteristics of the sample tested. For instance,  
154 it has been shown that the age range of the participants influences the RAN-reading  
155 relationship. Thus, as mentioned before, RAN appears to become a more powerful predictor for  
156 reading skills after Grade 3 (Parrila, Kirby & McQuarrie, 2004). Note that it is not clear whether  
157 the variable of interest corresponds to the chronological age of the participants, or to their  
158 degree of expertise in literacy as both usually co-vary. Reading level and age are commonly  
159 confounded into grade information. Age and reading level indeed share common variance, but  
160 they do not share a one to one relationship. Previous studies (deJong, 2011) reported that the  
161 better readers of sample were among the younger children, however classification by reading  
162 level were highly similar to classification by age, resulting in the intensive use of grade  
163 information for comparing readers. Here we orthogonalize age and reading expertise in order  
164 to tease out the contribution of age versus reading skills to the behavioral RAN-reading  
165 relationship and to the neurophysiological changes in the discrete letter and picture RAN.

166  
167 To our knowledge there are no published studies involving children and using ERP recordings  
168 during discrete letter RAN or discrete letter naming, but a few studies involving children used  
169 ERP or MEG recordings during picture naming, a task that is close to discrete picture RAN.  
170 We are not aware of a study comparing readers varying in their expertise in a typically  
171 developing sample. The two studies using ERP or MEG recordings during picture naming  
172 compared typical and dyslexic readers. Greenham, Stelmack, and van der Vlugt (2003) and  
173 Trauzettel-Klosinski, Dürrwächter, Klosinski, & Braun, (2006) both reported increased error  
174 rates and longer reaction times in dyslexic participants relative to typically developed (TD)  
175 participants, but no electrophysiological correlates of these differences were observed in the

176 picture naming task. As ERP differences were found across groups in the reading tasks, but not  
177 in picture naming, the authors suggested that the “visual” pathway is somehow preserved in  
178 dyslexic participants, at least in the early stages of picture processing. Greenham et al. (2003)  
179 hypothesized that electrophysiological differences between dyslexic and TD participants may  
180 be observed in later ERP time-windows, beyond the 500 ms analyzed in that study, possibly  
181 closer to articulation and associated with phonological processes. Consequently, an  
182 investigation of the electrophysiological correlates in a discrete RAN task taking should into  
183 account longer time-intervals than those used in these studies. Regarding the effect of age on  
184 the electrophysiological correlates of picture naming, a longitudinal study (Ojima, Matsuba-  
185 Kurita, Nakamura, Hoshino, & Hagiwara, 2011) using the picture-word interference task, found  
186 similar ERP components in 7 and 9 year-old children and in adults, but with shifts of latencies.  
187 The authors concluded that the differences in reaction times observed between children and  
188 adults rely on an acceleration of the processes subtending the task. Laganaro, Tzieropoulos,  
189 Frauenfelder, & Zesiger (2015) compared the ERPs of typically developing 7-8 year-olds, 10-  
190 12 year-olds, and adults on an overt picture naming task. The results on the two groups of  
191 children, showed that the speeding up observed in word production does not seem to rely on a  
192 linear rescaling of all ERP components, but on a selective shortening in the time-window  
193 usually associated with lexico-phonological encoding processes.

194  
195 Hence, the previous ERP results on discrete picture RAN like tasks (picture naming tasks)  
196 reported electrophysiological differences between younger and older school-age children,  
197 whereas surprisingly no modulation of ERPs was reported in picture naming tasks between  
198 dyslexic and TD readers, suggesting that reading skills do not modulate the electrophysiological  
199 correlates at least for discrete picture RAN. However, the contrast of dyslexic and typically  
200 developing children on reading level is a special case, which may not capture the RAN-reading  
201 relationship underlying typical reading acquisition. Here we take advantage of the variability  
202 within typically developing children to test with an orthogonal design in children aged 7 to 10  
203 years:

204 1) to which extend the RAN-reading relationship is modulated (a) by the participants’ age, and  
205 (b) by the participants’ reading level? and

206 2) whether the ERP signal from discrete picture and letter RAN tasks differentiates younger  
207 and older, or poorer and better readers among typically developing children.

208 Contrary to behavioral approaches which do not give insight on the specific processing stages  
209 at work during a discrete RAN task and responsible for the relationship between RAN and  
210 reading, the ERP recordings during discrete RAN tasks will inform on whether age and reading  
211 level effects are sustained by different mental processes. Indeed, previous studies using reaction  
212 times and error rates did not get to differentiate age and reading level (Catts, Gillispie, Leonard,  
213 Kail, & Miller, 2002; de Jong, 2011; Parrila, Kirby & McQuarrie, 2004) as the RAN-reading  
214 relationship remained constant in both cases. At the electrophysiological level, specific  
215 hypotheses can be made: age should be reflected in the ERP signal by the global acceleration  
216 of processing (Ojima et al., 2011), whereas the relationship between RAN and reading level  
217 should be observed in specific time-windows reflecting specific processing stages (i.e. lexical  
218 access and/or phonological encoding).

219

220

## 221 2. Material and Method

222

### 223 *Participants*

224 32 French-speaking children were selected from a larger group of 62 participants according to  
225 their age and reading skills. They were typically developing children, attending schools of the

226 Geneva area. Recruitment was done through announcements on the University website.  
227 Children were tested individually in our lab, with two experimenters for the EEG session and  
228 one for the behavioral session. The local research ethical committee approved the study  
229 protocol. Written informed consents were collected from the children and their parents. At the  
230 end of the experimental session, the children received a small present and a voucher for their  
231 participation. The study protocol was in accordance with the Declaration of Helsinki.

232  
233 Among the 32 participants, two orthogonal groups were constituted, based on age and on  
234 reading skills. There were no outliers in the selected sub-sample of children. Among  
235 participants, 8 were age-low; reading-low – 8 were age-high; reading-low – 8 were age-low;  
236 reading-high – and 8 were age-high; reading-high. The same 32 participants were split into two  
237 groups according to age but matched on reading skills and according to reading skills but  
238 matched on age. Poor and good readers were identified based on Text reading scores (word  
239 correctly read per minute). Poor readers obtained Text reading scores from 52 to 99 words  
240 correctly read per minutes whereas good readers obtained scores ranging from 116 to 172 words  
241 correctly read per minute. For age, two groups of 16 participants matched on reading skills, but  
242 differing on age were constituted (see Table 1). In each age group, half of the participants were  
243 good readers, and the other half were poor readers. This allowed constituting two reading skill  
244 groups (good and poor readers) of 16 participants each, who differed on reading skills for all  
245 the reading measures but were matched on age (see Table 2).

246 -----  
247 Tables 1 & 2  
248 -----

249  
250 *Task and material*

251  
252 **Reading measure**

253 *Text reading*

254 Text reading was assessed by using the test "Monsieur Petit" extracted from the "Evaluation de  
255 la Fluence en Lecture" battery (E.L.F.E, Lequette, Pouget, & Zorman, 2008). In this test,  
256 children are instructed to read aloud as fast and accurately as possible a text containing 24 lines  
257 and 352 words. The experimenter asks them to stop after one minute. The text reading score is  
258 the number of words correctly read within one minute.

259  
260 ***Discrete reading***

261 16 monosyllabic words were selected from the French lexical database Manulex (Lété,  
262 Sprenger-Charolles, & Colé, 2004). All words were four to six letter long with an average print  
263 lexical frequency of 115.6 per million. Changing at least two letters in the set of words created  
264 eight orthographically legal and pronounceable pseudowords. The stimuli were displayed on a  
265 computer screen using the software E-prime (E-studio). Each trial began with a fixation cross  
266 presented for 500 ms at the center of the screen. The fixation cross was then replaced by a grey  
267 screen for 200 ms, followed by the word for 2000 ms in the middle of the screen. The fixation  
268 cross-picture sequence was manually triggered by an experimenter sitting behind the child. The  
269 children were asked to read aloud the words and pseudowords as fast and accurately as possible.  
270 The task was divided into two parts: word reading (with the 16 words repeated each 5 times)  
271 and pseudoword reading (with the 8 pseudowords repeated each 5 times). By dividing the  
272 number of correct responses by the mean reaction time a composite discrete reading score was  
273 computed.

274  
275 **Phonological awareness**

276 The phonological awareness tasks were borrowed from the Odedys battery (i.e., spoonerism  
277 task; Jacquier-Roux, Valdois, & Zorman, 2005), and from the Isadyle battery (i.e., initial  
278 phoneme deletion task; Piérart, Mousty, Grégoire, & Comblain, 2010). The two PA scores  
279 correspond to the number of correct responses in each task (out of 8 trials for the spoonerism  
280 task, and 10 trials for the phoneme deletion task).

281

## 282 **RAN**

283 Serial tasks: Picture and Letter

284 For both tasks, the child was asked to name as fast and accurately as possible the items displayed  
285 on an A4 sheet (landscape orientation). Responses were digitally recorded. A speech analysis  
286 software (Praat: doing phonetics by computer, Boersma & Weenink, 2013) was used to measure  
287 the total time taken by the child to name all the items for each grid.

288

289 Pictures: 16 black and white drawings and their corresponding modal names were selected from  
290 French databases (Alario & Ferrand, 1999; Bonin, Peerman, Malardier, Méot, & Chalard,  
291 2003). The stimuli corresponded to 16 words with an age of acquisition range of 1.31 - 2.95 on  
292 a five-point scale (1: learned between 0 and 3 years; 4: learned between 9 and 12 years) and  
293 high name agreement (mean = 93.6 %) to ensure that the children give the same name for a  
294 same picture. They were displayed on two A4 sheets, with 3 repetitions of each item (24 stimuli  
295 per grid). A familiarization trial with all pictures and their corresponding modal names was  
296 carried out prior to running the experiment.

297 Letters: 16 letters were selected as a function of to their syllable frequency and letter frequency  
298 characteristics. Stimuli were displayed on two A4 sheets, with 3 repetitions of each item (24  
299 stimuli per sheet).

300

301 Discrete tasks

302 The same stimuli as those used in the serial RAN tasks were displayed one by one on a computer  
303 screen using the software E-prime (E-studio). These tasks were performed under EEG  
304 recording. Each trial began with a fixation cross, presented for 500 ms in the center of the  
305 screen, then a grey screen for 200 ms followed by the stimulus. The duration of the presentation  
306 varied across tasks (i.e. 2000 ms for the pictures, and 800 ms for the letters). In order to avoid  
307 recording EEG when the signal was noisy due to the child's movements, an experimenter sitting  
308 behind the child, who was in visual contact with the other experimenter monitoring the online  
309 EEG signal, manually triggered the trials. The children were asked to name aloud the pictures  
310 and letters as fast and accurately as possible. Word productions were digitally recorded and  
311 production latencies (i.e. the time separating the onset of the picture and the onset of the speech  
312 wave) were systematically computed with a speech analysis software (Check-Vocal,  
313 Protopapas, 2007). The discrete RAN scores comprise the average RTs and the number of  
314 correct responses per stimuli type.

315

316 *EEG acquisition and pre-analyses:*

317 EEG was recorded continuously during discrete RAN tasks using the Active-Two Biosemi EEG  
318 system (Biosemi V.O.F. Amsterdam, Netherlands) with 64 channels covering the entire scalp.  
319 Signals were sampled at 512 Hz (filters: DC to 104 Hz, 3 dB/octave slope). The common mode  
320 sense (CMS; active electrode) – driven right leg (CMS-DRL) is the online reference in the  
321 Biosemi system. Offline, ERPs were then bandpass-filtered to 0.2–30 Hz and notch-filtered to  
322 50 Hz and re-referenced to the average reference. Epochs were extracted locked to the stimulus  
323 (the word, the picture, the letter) with different duration according to the production latencies  
324 in each task. Average reaction times were 955 ms for picture naming and 683 ms for letter  
325 naming. Epochs were extracted from -50 to 400 time-frames (i.e. 798 ms) in the discrete picture



326 RAN and epochs from -50 to 250 time-frames (i.e 488 ms) for the discrete letter RAN. Epochs  
327 contaminated by eye blinking, eye-movements, movements or other noise were rejected and  
328 excluded from averaging after visual inspection. Baseline correction was applied based on the  
329 100 ms pre-stimulus interval. Only trials with correct responses and valid RTs were retained.  
330 Epoch extraction and averaging was computed for each participant using the Cartool software  
331 (Brunet, Murray, & Michel, 2011). As a result, an average of 64 averaged trials per participant  
332 and per task entered the ERP analyses (range: 42-78). Electrodes with signal artifacts were  
333 interpolated using 3-D splines interpolation (Perrin, Pernier, Bertrand, Giard, & Echallier,  
334 1987), with an average of 8 sites interpolated for each participant.

335

### 336 3. Results

337

#### 338 *Behavioral results*

339 In order to diminish the number of variables, the  $z$ -score values of the six RAN indexes (serial  
340 picture RAN total time, serial letter RAN total time, discrete picture RAN mean reaction time  
341 and number of correct responses, discrete letter RAN mean reaction time and number of correct  
342 responses) were entered into a Factorial analysis (principal component using promax rotation  
343 with Kaiser normalization, SPSS software). Two components were extracted representing a  
344 total of 66.9% of explained variance. As can be seen in Table 3, the loadings of the first  
345 component, which explains 41.4% of variance, are mostly related to the picture RAN variables.  
346 This component was therefore labeled Picture RAN factor. The second component, explaining  
347 25.4% of variance, is more strongly related to the letter RAN variables, and was consequently  
348 labeled Letter RAN factor. A similar analysis was performed with the two Phonological  
349 Awareness tasks, the Phoneme deletion task and the Acronym task ( $z$ -score values). The Factor  
350 extracted explains 64.4% of the variance, and the loading of each variable was .802.

351

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Table 3  
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356 We then tested whether these factors would allow discriminating the participants as a function  
357 of their age and reading level. We thus performed a multiple analysis of variance comparing  
358 the performance of the participants by Age (younger vs. older) and Reading level (good vs.  
359 poor) with the 3 factors representing the RAN and the PA tasks as dependent variables. The  
360 results reveal a significant main effect of Age,  $F(3,26)= 4.207, p = .015$ , and of Reading level,  
361  $F(3,26)= 4.513, p = .011$ . The Age X Reading level interaction does not reach significance  
362 ( $p>.3$ ). Table 4 reports the effects of Age and Reading level variable by variable. It can be seen  
363 that the effect of Age is significant only on the Letter RAN factor. By contrast, the effect of  
364 Reading level is highly significant on the Picture RAN factor, and a trend is observed on the  
365 other two factors.

366

367

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370

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Table 4  
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371 Finally, two regression analyses were performed to test which variables predicted reading level.  
372 In both analyses, the predictors were the two RAN factors, the PA factor and Chronological  
373 age. In the first analysis, the dependent variable was Text reading fluency. The results show  
374 that this variable is only predicted by the Letter RAN factor,  $F(1,30)=6.64, p=.015, R^2 = .194$ .  
375 The second analysis had a composite measure of discrete reading (which combines RT and

376 number of correct responses) as a dependent variable. The results indicate that both the Picture  
377 RAN factor,  $F(1,30)=10.90, p=.002, R^2 = .242$ , and Chronological Age,  $F^A(1,29)=7.17, p=.012,$   
378  $R^{2\Delta} = .145$ , contribute to explain the variance of discrete reading.

379  
380 *ERP results*

381 The ERPs of Discrete picture RAN and Discrete letter RAN were subjected to standard  
382 waveform analysis to determine the time periods of amplitude differences between age groups  
383 and reading-performance-groups. This analysis was performed on all electrodes and data-  
384 points. One-way analyses of variance (ANOVA) were computed on amplitudes of the evoked  
385 potentials between groups using the STEN toolbox (developed by Jean-François Knebel;  
386 <http://www.unil.ch/fenl/home/menuguid/infrastructure/software-analysis-tools.html>). Only  
387 differences over at least four clustered electrodes and extending over at least 10 consecutive  
388 time-frames (i.e., 20 ms) were retained with an alpha criterion of 0.05.

389  
390 Figure 1 shows time points of significant amplitude differences between younger and older  
391 children for the two RAN tasks. For Discrete picture RAN (Figure 1A), significant differences  
392 appeared between younger and older children from 400 ms after stimulus presentation, and  
393 extend until 750 ms. Concerning Discrete letter RAN (Figure 1B), significant differences across  
394 age-groups are observed from 160 ms to 190 ms and from 350 ms to 410 ms after stimulus  
395 presentation). In both tasks amplitudes were more negative on posterior electrodes (see O1  
396 displayed on Figure 1A and 1B) for the younger group.

397  
398 Figure 2 shows the time-points of significant amplitude differences between good and poor  
399 readers. In the discrete picture RAN task (Figure 2-A), significant differences between good  
400 and poor readers appeared in the N2 time-interval (i.e. 200-250 ms) on a large cluster of central-  
401 anterior channels and in a short later time-window (i.e. from 380 ms to 410 ms after stimulus  
402 presentation) on a small cluster of electrodes In the N2 time-interval amplitudes were more  
403 negative on posterior electrodes for poor readers (see Figure 2A). No significant differences  
404 between good and poor readers were found in the Discrete letter RAN task (Figure 2B).

405 -----  
406 Figure 1 & 2  
407 -----

408  
409 4. Discussion

410  
411 In this study we investigated whether the RAN-reading relationship is modulated (a) by the  
412 participants' reading level, and (b) by the participants' age among a sample of typically  
413 developing children, and whether the ERP signal from a discrete RAN task differentiates  
414 younger and older, and/or poor and good readers. For this purpose, we developed a design in  
415 which two groups of children were matched on age to investigate the impact of reading skills,  
416 or on reading skills to investigate the impact of age.

417  
418 *Age effect*

419 The behavioral results revealed that young and older children differ in their performance on the  
420 letter RAN, with slower naming times for younger children, whereas no age differences  
421 appeared on the picture RAN and the PA factors on groups matched on reading skills. The  
422 effect of age limited to the letter RAN task advocates for a stimulus effect between younger in  
423 older children. Given that both Age groups do not differ in reading level, this effect is more  
424 likely dependent on the duration of exposure to the written code than on reading expertise *per*  
425 *se*. In any case, these results suggest that the letter RAN is more sensitive to age differences

426 than the picture RAN. Interestingly, our results show that PA skills do not seem to vary  
427 according to the age of the participants, at least within the age range tested in this study.  
428 Actually, participants perform very well in PA tasks, resulting in high scores and low variability  
429 within the sample, which can explain the absence of PA effect according to age. Some authors  
430 (ref.) have previously proposed that PA accuracy cannot differentiate groups of participants in  
431 a typically developed sample. Indeed, children perform too well in PA tasks after the early  
432 grades. The difference in PA skills between groups could be expressed at the reaction time  
433 level, as every children can give the right answer, but older ones are faster.

434  
435 We found also specific time-intervals in the ERP signal in Discrete RAN tasks modulated by  
436 age. In the discrete letter RAN task, the first differences between younger and older children  
437 appeared in the N170 time-window with larger amplitudes for younger children. This result is  
438 in line with a stronger sensitivity to print in older children (Maurer et al., 2006) and with the  
439 behavioral results reported earlier. Crucially, we found more extended and later (from 400 ms  
440 to 750 ms) electrophysiological differences between younger and older children in the discrete  
441 picture RAN. Overall, these results suggest that the entire time-course of discrete picture and  
442 letter RAN develops across age

#### 443 444 *Reading skill effect*

445 At the behavioral level, good and poor readers differed mainly in their performance on the  
446 picture RAN factor, although a trend was also observed on the letter RAN and on the PA factors.  
447 These results suggest that picture RAN is a better index of reading level variance than  
448 alphanumeric RAN, a result that is in line with those of Arnell et al. (2009). It however runs  
449 against the dominant view that alphanumeric RAN is a stronger predictor of reading skills than  
450 RAN tasks using other stimuli (Manis & Doi, 1995; Misra, Katzir, Wolf, & Poldrack, 2004;  
451 Savage et al., 2007; Schatschneider et al., 2004). Direct comparison of the present results with  
452 these previous studies should nevertheless be done with caution given the fact that our picture  
453 RAN factor is a composite measure that involves mostly, but not exclusively, picture RAN, and  
454 is based both on serial and discrete versions of the RAN task. In the two regressions analysis,  
455 we investigated which factor predicts reading skills both in terms of text reading and of discrete  
456 reading. Results showed a clear-cut difference between the two types of reading assessments.  
457 Indeed, text reading variance is predicted by the Letter RAN factor only whereas discrete  
458 reading variance is predicted by both the Picture RAN factor and age.

459 The previously reported alphanumeric superiority at the behavioral level in the RAN-reading  
460 relationship could be explain by the type of reading tasks used in previous studies. Indeed,  
461 previous studies mostly used text reading to address reading fluency, which may led to the  
462 systematic distinction between predictive powers of letter and picture RAN (see Kirby et al.,  
463 2010 for review). During text reading, participants rely on context to predict the next words,  
464 the prediction of the words to come is based on both context and first letter of the word. Thus  
465 it is expected that this type of processes relate more with letter RAN. During a discrete reading  
466 task, the use of context and first letters to guess what word will be displayed next is impossible.  
467 Therefore, discrete reading task are by nature more similar to picture naming task as they both  
468 require the retrieval of a phonological form from visual information taken at once. The present  
469 results advocate for caution when selecting the reading task according to the hypothesis to be  
470 tested, as text and discrete reading appear to be different task by nature.

471 Again, the PA factor does not predict reading skills variance in our sample. Cronin (2011)  
472 argued that the long lasting predictive power of PA across elementary grades is specific to  
473 English, which behaves as an “outlier” among European languages (Share, 2008). Studies in  
474 transparent orthographies (Lepola, Poskiparta, Laakkonen, & Niemi, 2005; Manis, Seidenberg,  
475 & Doi, 1999; Verhagen, Aarnoutse, & van Leeuwe, 2008; Wagner, Torgesen, & Rashotte, 1994;

476 Wimmer et al., 2000) reported that PA predicts reading skills only through second grade, which  
477 is similar to our results. Note that French is considered as a mid-opaque orthographic system.

478  
479 Our results suggest that letter and picture RAN do not address the exact same processing stages  
480 as they relate differently to reading tasks. Moreover, it confirms that the format of the reading  
481 task seems to be crucial when investigating the RAN-reading relationship as advocated by  
482 deJong (2011). Indeed, previous studies reporting an alphanumeric superiority in the RAN-  
483 reading relationship (Savage et al., 2007; Schatschneider et al., 2004) are mostly based on text  
484 reading or on a reading assessment combining both text and word reading.

485  
486 When children are divided into groups according to their reading level but matched on age,  
487 group differences in ERPs are limited to the discrete picture RAN task. In the discrete picture  
488 RAN ERPs, poor readers exhibited larger amplitudes than good readers around 200 ms,  
489 corresponding to a N170/N200 component and lower amplitudes around 400ms after the picture  
490 onset on screen. The N170 interval in picture naming has been associated with recognition of  
491 the picture and conceptual/semantic processes (Indefrey, 2011; Schendan & Kutas, 2003). The  
492 second time-window falls within a P2 component (see Figure 2), although it is clearly delayed  
493 in the present study relative to studies with adult participants. A similar delay of component  
494 was previously reported in studies with children (Laganaro, Tzieropoulos, Frauenfelder, &  
495 Zesiger, 2015; Trauzettel-Klosinski, Dürrwächter, Klosinski, & Braun, 2006). If one  
496 proportionally rescales adult's time-course estimates taking this delay into account, the second  
497 positive component peaking in the youngest children around 400 ms could be interpreted as a  
498 P2. Modulations of amplitudes within the P2 time-interval have been previously associated with  
499 frequency effects in picture naming studies involving adults (Strijkers, Holcomb, & Costa,  
500 2012) and the P2 component has been associated with lexical selection (Indefrey, 2011). The  
501 differences in waveform amplitudes around the P2 component and beyond may therefore reflect  
502 differences in lexical selection and phonological encoding between good and poor readers.

503  
504 The present results diverge from those of previous studies using ERP/MEG recordings during  
505 picture naming with groups of children varying in their reading expertise (Greenham, Stelmack,  
506 & van der Vlugt, 2003; Trauzettel-Klosinski, Dürrwächter, Klosinski, & Braun, 2006) which  
507 did not report ERP differences between groups (see Introduction). Here we found specific time-  
508 intervals in the picture naming task differentiating poor and good readers. Contrary to the  
509 hypothesis made by Greenham and colleagues that ERP differences between time-windows  
510 differentiating TD and dyslexic participants should appear beyond 500 ms after stimulus  
511 presentation, we reported differences as soon as the N2 component. It should be noted that  
512 comparison between the present results and results reported by Greeham and colleagues (2003)  
513 should be done with caution. In fact, Greenham and colleagues used a picture-word interference  
514 paradigm, which is different from the bare picture naming task used here. Also, previous studies  
515 had rather small samples sizes (i.e. 8-13 subjects in each group), which can explain the lack of  
516 differences between groups in picture naming.

#### 517 518 *Age and reading skills in the RAN-reading relationship*

519 Previous studies reported an alphanumeric superiority effect on the RAN-reading relationship  
520 (Manis & Doi, 1995; Misra, Katzir, Wolf, & Poldrack, 2004; Savage et al., 2007;  
521 Schatschneider et al., 2004). Our behavioral and ERP results converge in suggesting that the  
522 alphanumeric superiority is a matter of age more than a matter of reading efficiency, and is  
523 probably subtended by a longer exposure to printed information. The age by reading level  
524 interaction did not reach significance for any of the three factors entered in the analysis, which  
525 indicates that reading level and age effects are fairly independent from each other. In addition

526 only age modulated ERPs in the letter RAN. By contrast, picture RAN performance and specific  
527 processing stages indexed by the ERP signal in picture RAN are highly related to both reading  
528 skills and age. Taken together the present results at both the behavioral and the  
529 electrophysiological levels give new insights on the RAN-reading relationship. First, it clearly  
530 appear that age and reading efficiency, even though they co-vary, do not represent the same  
531 concept. Apparently, age cannot be used as a proxy for reading efficiency, at least in French.  
532 Secondly, the alphanumeric superiority previously reported in the literature on the RAN-  
533 reading relationship seems to be balanced by the present findings suggesting that alphanumeric  
534 RAN captures cognitive changes related to age but not to reading level. Indeed, alphanumeric  
535 RAN scores reflect the degree of automation of closed-class stimuli (i.e. letters). Moreover,  
536 knowing the letter's names is not a good indicator of reading skills once formal reading  
537 instruction began, but knowing the letter's phoneme correspondence is (Blaiklock, 2004).  
538 Third, we propose that picture RAN is related to reading level because of lexical access and  
539 lexico-phonological binding stages. Poor and good readers differ specifically on two  
540 components: the N170 and the P2, reflecting early lexical access and lexico-phonological  
541 binding in the reading literature (Maurer et al., 2006). In the picture naming time-course, the  
542 P2 component is usually associated with lexical access (Indefrey, 2011) and the N170-like  
543 component seems to be specific to children (Laganaro et al., 2014). Here we report differences  
544 between good and poor readers in these two specific time-intervals, suggesting that the  
545 processing stages taking place between 200 and 500 ms in picture RAN are the cornerstone of  
546 the RAN-reading relationship. Moreover, we argue that lexical access stage is not present in  
547 letter naming – at least not in the same sense as in picture naming or reading – which explains  
548 the absence of reading effect on letter RAN (Grainger, Rey, & Dufau, 2008; Madec, Rey,  
549 Dufau, Klein, & Grainger, 2012).

550

### 551 *Conclusion*

552 To our knowledge, this study is the first to compare younger and older children as well as good  
553 and poor readers in a sample of typically developing children on their performance in various  
554 RAN and reading tasks and to report ERP modulation by age and reading level on discrete RAN  
555 tasks. Discrete letter RAN processes appeared to be modulated by the participant's age, whereas  
556 processes tackled by the picture RAN task seem to be modulated both by the participant's  
557 reading expertise and by age. This suggests that there are specific processes tackled by the  
558 discrete picture RAN task that are likely to constitute the cornerstone of the RAN-reading  
559 relationship whereas discrete letter RAN tasks are sensitive to the duration of exposure to the  
560 written code. Future studies dedicated to the investigation of the RAN-reading relationship  
561 should investigate which cognitive processes underlie these specific relationships between  
562 RAN task format and age versus reading skills.

563

### 564 *Author contribution*

565 Each author has participated sufficiently in the work to take responsibility for certain portions  
566 of the manuscript's content. MC made substantial contributions to conception and design, data  
567 collection and analysis and interpretation of the data. GM made significant contributions to data  
568 collection and analysis and to interpretation of the data. ML made considerable contribution to  
569 conception and design and to analysis and interpretation of the data. PZ made significant  
570 contribution to conception and design and to analysis and interpretation of the data.

571

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574

575

576 Conflict of interest: none.

577

578

579 Table 1. Participants divided into age groups (i.e., younger and older children)

	Age	Text reading (nb of words read/ minute)	Text reading z-score	Discrete reading RTs (ms)	Discrete reading accuracy (%)
Young children	8.0 ( $\pm$ .69)	104.88 ( $\pm$ 39.92)	.8 ( $\pm$ .4)	835 ( $\pm$ 127)	82 ( $\pm$ 10)
Older children	9.68 ( $\pm$ .48)	119.69 ( $\pm$ 40.41)	.88 ( $\pm$ .42)	810 ( $\pm$ 120)	88 ( $\pm$ 9)
P value	< .001	> .31	> .60	> .58	> .10

580

581

582 Table 2. Participants divided into reading skills groups (i.e., poor and good readers)

	Age	Text reading (nb of words read/ minute)	Text reading z-score	Discrete reading RTs (ms)	Discrete reading accuracy (%)
Poor readers	8.66 ( $\pm$ 1.17)	76.5 ( $\pm$ 16.26)	.5 ( $\pm$ .18)	878 ( $\pm$ 104)	79 ( $\pm$ 10)
Good readers	9.02 ( $\pm$ .88)	148.06 ( $\pm$ 18.67)	1.18 ( $\pm$ .24)	768 ( $\pm$ 117)	91 ( $\pm$ 5)
P value	> .34	< .001	< .001	< .001	< .001

583

584

585 Table 3. Structure matrix for the principal component analysis performed on the RAN variables.

	Component	
	1	2
Serial RAN Picture total time	.876	.198
Serial RAN Letter total time	.308	.870
Discrete RAN Picture Correct responses	-.838	-.203
Discrete RAN Picture Mean RT	.607	.066
Discrete RAN Letter Correct responses	-.542	-.662
Discrete RAN Letter Mean RT	-.082	.848

587

588

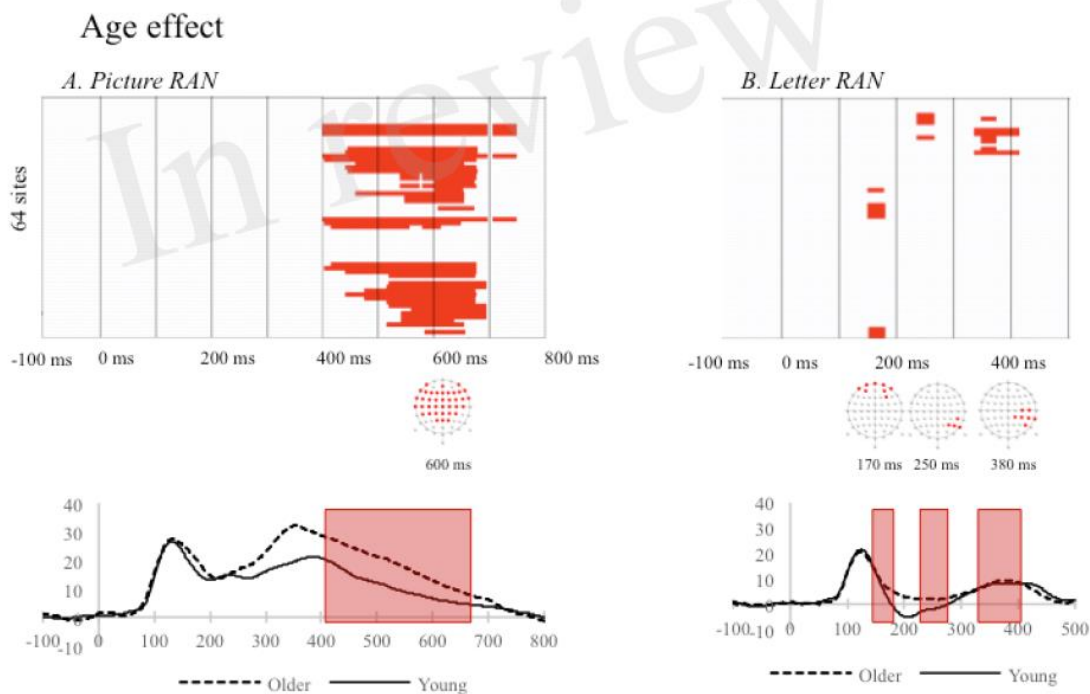
589 Table 4. Results of the multiple analysis of variance as a function of Age and Reading level per variable.

Factor	Variable	<i>F</i>	<i>df</i>	<i>p</i>	<i>etasqu</i>
Age	Factor RAN Picture	.129	1,28	.722	.005
	Factor RAN Letter	12.560	1,28	.001	.310
	Factor PA	.190	1,28	.666	.007
Reading level	Factor RAN Picture	10.822	1,28	.003	.279

Factor RAN Letter	3.177	1,28	.086	.102
Factor PA	3.373	1,28	.077	.108

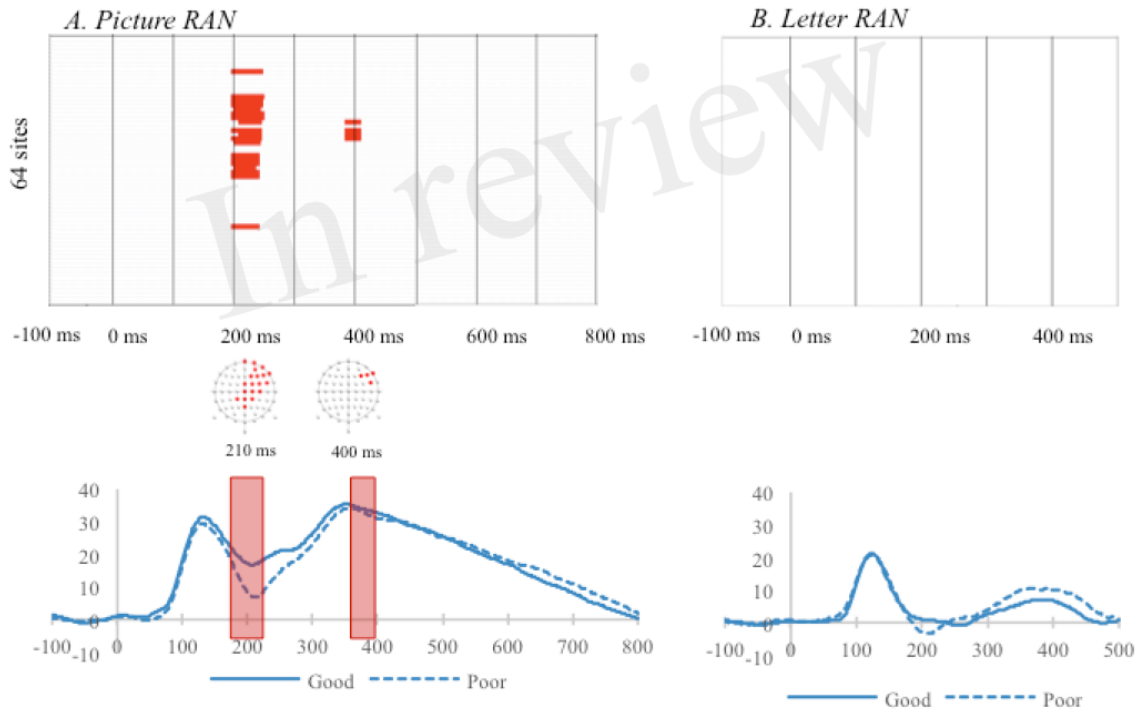
591 Note: the Age by Reading level interaction does not reach significance on any of the  
592 variables, all  $ps > .13$

593  
594 Figure 1. Significant differences on ERP waveform amplitudes for each electrode (y axes) and  
595 time-point (x-axes) between younger and older children for the two discrete RAN tasks: discrete  
596 picture RAN (Fig. 1A) and discrete letter RAN, (Fig. 1B). Only differences over at least four  
597 clustered electrodes and 10 time frames, with an alpha criterion of .05 are displayed in red. The  
598 channel yielding the significant differences of amplitudes and an example waveform is  
599 displayed under each graph (O1) with time-windows of significant effects displayed with a red  
600 shape. (For interpretation of the reference to color in this figure legend, the reader is referred to  
601 the web version of this article.)



602  
603  
604 Figure 2. Significant differences on ERP waveform amplitudes for each electrode (y axes)  
605 and time-point (x-axes) between poor and good readers for the two discrete RAN tasks: discrete  
606 picture RAN (Fig. 2A) and discrete letter RAN (Fig. 2B). Only differences over at least four  
607 clustered electrodes and 10 time frames, with an alpha criterion of .05 are displayed in red. The  
608 channel yielding the significant differences of amplitudes and an example waveform is  
609 displayed under the graph (PO3) with time-windows of significant effects displayed with a red  
610 shape. (For interpretation of the reference to color in this figure legend, the reader is referred to  
611 the web version of this article.)

# Reading Level effect



612  
613



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