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HAL Authorization

1 A sensorimotor representation impairment in dyslexic adults: a specific profile  
2 of comorbidity.

3

Rebecca Marchetti<sup>a,b,c</sup>, Marianne Vaugoyeau<sup>a,c</sup>, Pascale Colé<sup>b,c</sup>, Christine Assaiante<sup>a,c</sup>

a Aix-Marseille Université, CNRS, LNC UMR 7291, Marseille, France.

b Aix-Marseille Université, LPC UMR 7290, Marseille, France

c Aix Marseille Université, CNRS, Fédération 3C, Marseille, France

**Corresponding authors:**

[rebecca.marchetti@univ-amu.fr](mailto:rebecca.marchetti@univ-amu.fr) (RM)

[marianne.vaugoyeau@univ-amu.fr](mailto:marianne.vaugoyeau@univ-amu.fr) (MV)

## 4 **Abstract**

5 Sensorimotor disorders have been frequently reported in children and adults with dyslexia over the past  
6 30 years. The present study aimed to determine the impact of sensorimotor comorbidity risks in dyslexia  
7 by investigating the functional links between phonological and sensorimotor representations in young  
8 dyslexic adults. Using 52 dyslexic participants and 58 normo-readers, we investigated whether the  
9 underlying phonological deficit, which is reported in the literature, was associated with a general  
10 impairment of sensorimotor representations of articulatory and bodily actions. Internal action  
11 representations were explored through motor imagery tasks, consisting of measuring and comparing the  
12 durations of performed or imagined actions chosen from their current repertoire of daily life activities.  
13 To detect sensorimotor deficits, all participants completed the extended version of the M-ABC 2, as a  
14 reference test. We found sensorimotor impairments in 27% of the young adult dyslexics, then considered  
15 as sensorimotor comorbid, as opposed to much less in the normo-reader group (5%). While motor  
16 slowdown, reflecting motor difficulty, was present in all dyslexic adults, motor imagery performance  
17 was impacted only in the specific dyslexic subgroup with sensorimotor impairments. Moreover, in  
18 contrast with slowness, only the comorbid subgroup showed an increased variability in execution  
19 durations. The present study highlights the importance of the quality of perception-action coupling,  
20 questions the relevance of investigating sensorimotor impairment profiles beyond phonological deficits  
21 and provides new arguments supporting the perspective of multiple deficits approaches in dyslexia.

## 22 **Keywords**

23 Sensorimotor comorbidity; M-ABC2; internal representation of action; motor imagery tasks; dyslexic  
24 young adults

25

26

## 27 **Highlights**

- 28 1. A high incidence of co-morbidity between dyslexia and sensorimotor disorders has been observed  
29 in young adults.
- 30 2. Motor slowdown and execution variability reflecting motor difficulty are reported in dyslexic  
31 adults.
- 32 3. Isochrony between overt and covert actions is present in dyslexic and normo-reader adults.
- 33 4. Internal representations of action are specifically affected in dyslexics with sensorimotor deficits.
- 34 5. The efficiency of updating an internal model is preserved in dyslexic adults.

## 36 **Introduction**

37 Developmental dyslexia (hereafter dyslexia) is a lifelong impairment, typically identified by reading  
38 deficits, affecting 6% to 8% of the French population (De la Haye et al., 2011; Jonas, 2012). As it is a  
39 developmental disorder and not a simple delay (Habib 2000), the difficulties experienced by individuals  
40 with dyslexia do not suddenly stop once reaching adulthood (Cavalli et al., 2018; Nergard-Nilsen &  
41 Hulme 2014; Ramus et al., 2003a; Swanson & Hsieh, 2009) and it is now well-known that these  
42 difficulties impact their lives much more widely than just in academic achievement (Davis et al. 2008;  
43 Humphrey 2002; Macdonald & Deacon 2018; Nalawałny et al., 2017).

44 Given the widespread incidence of dyslexia, we can rely on decades of research and an extensive  
45 literature on the impact of dyslexia and its causes. In this context, the influence of the phonological  
46 theory has increased over the past 30 years and today the phonological impairment appears to be core  
47 in dyslexic disorders (Cavalli et al., 2018; Ramus & Szenkowitz 2008; Shaywitz and Shaywitz, 2005;  
48 Vellutino (et al.) and Fletcher, 2004; Ramus et al., 2003a; Snowling, 2000). Nevertheless, reading is a  
49 complex ability that requires perfect coordination between neural systems and supporting visual,  
50 auditory, language and motor process (Stoodley and Stein, 2013), and this may explain why the  
51 phonological impairment is frequently associated with other disorders.

52 As soon as 2003, Ramus and colleagues introduced the problem of heterogeneity and complexity of the  
53 manifestation of developmental dyslexia in two seminal papers (Ramus et al., 2003a and b). Indeed, the  
54 presence of sensorimotor deficits in dyslexia has been reported in previous studies and would affect one  
55 out of two dyslexic children (Ramus et al., 2003b), and one out of four dyslexic adults (Ramus et al.,  
56 2003a), as confirmed by a recent review (Blank et al., 2019). Arguments in support of the sensorimotor  
57 deficits in dyslexia come from postural, oculomotor, motor coordination, and implicit motor learning  
58 disorders reported in dyslexic children and adults (Cignetti et al., 2018; Nicolson and Fawcett, 1999;  
59 Ramus et al., 2003a and b). These disorders were extensively discussed for a long time, because the  
60 finding of a sensorimotor control automatization deficit in dyslexia was not consistent across studies,  
61 often based on small samples with a wide variety of methods used (Stoodley, 2016). Most probably, the  
62 comorbidity between dyslexia and other neurodevelopmental disorders such as Developmental  
63 Coordination Disorder may explain discrepancies and lively debates in the literature. Nevertheless, a  
64 consensus emerged that motor difficulties are present in part of the dyslexia population, even though  
65 larger in children than adults (Ramus et al., 2003b).

66

67 Within the context of embodied cognition, some proposals argue that phonemic representations are  
68 partly rooted, in the sensorimotor experience, with the phonemic units being partially driven by the  
69 internal simulation from action to perception (Pulvermüller et al., 2005; Schwartz et al., 2012). The  
70 strength of this perception-action coupling is also highlighted by various neurophysiological studies  
71 (Fadiga et al., 1995, Watkins et al., 2003, Scerrati et al., 2015), which show that pre-activation of visual  
72 and auditory inputs can be facilitated by the prior perception of a linguistic stimulus. Moreover, this  
73 functional perception-action coupling, as underpinned by the mirror neuron system (Rizzolatti et al.,  
74 2001; 2002), is established early in infancy and is the basis for the development of sensorimotor,  
75 cognitive, and social representations (Assaiante et al., 2014, see also Wilson and Knoblich, 2005).  
76 Sensorimotor representations play a key role in motor control, according to the theory of internal models  
77 (Miall and Wolpert, 1996; Wolpert et al., 1998), sensorimotor representations are needed to anticipate  
78 and act on one's environment.

79

80 A relevant paradigm to explore internal representation is to use motor imagery (MI) that mentally  
81 simulates motor actions. MI is a mental process during which a movement is mentally simulated without  
82 any apparent motor output (Jeannerod, 1995, see also Decety 2006 and Guillot et al., 2012). The mental  
83 simulation of movement is generated by internal forward models, which are neural networks that mimic  
84 the performed action by predicting a future sensorimotor state based on an efferent copy of the motor  
85 intention (Miall and Wolpert, 1996; Wolpert and Flanagan, 2001). Many neuroimaging studies have  
86 shown the overlap, during mentally simulation of actions, with networks, and regions involved in the  
87 actual realization of those actions, such as in the pre-motor cortex, supplementary motor area,  
88 somatosensory cortex, subcortical (such as the thalamus and the putamen) and cerebellar regions.  
89 Potential involvement of the primary motor cortex is still under debate, as it is inconsistently observed  
90 in the literature (see Héту et al., 2013, Hardwick et al., 2018 for a review).

91 Impairment of internal representations compromises the capacities for anticipation and learning and  
92 many studies reported deficits in the predictive control of eye movements, anticipatory postural  
93 adjustments, gait, or mental rotation in the developmental coordination disorder (DCD) population,  
94 characterized by difficulty in acquiring and executing of coordinated motor skills that significantly  
95 interfere with daily life and academic productivity, and support the ‘internal modeling deficit’  
96 hypothesis (Adams et al., 2014, 2017; Assaiante et al., 2019; Deconinck et al., 2009; Gabbard et Bobbio  
97 2011; Wilson et al., 2013). In the past, few studies conducted in DCD adults, without comorbidity  
98 evaluation, reported that motor imagery deficit may persist at least in a subgroup of subjects (Hyde et  
99 al., 2014). Beside lifelong acquired representations of already skilled actions, motor learning involves  
100 accessing the formation of new representations, where sensorimotor representations need to be updated.  
101 Predictive control enables online correction by comparing real sensory feedback with predicted sensory  
102 consequences, generated through a forward internal model and in the case of a mismatch, error signals  
103 allow the correction of the motor command in real time. Impairments in online correction have thus  
104 been observed in DCD children (Fuelscher et al., 2015; Hyde & Wilson, 2011, 2013), as well as poor  
105 natural disposition to sequence learning or motor adaptation (Kagerer et al., 2004; Lejeune et al., 2016;  
106 Zwicker et al., 2011; see Biotteau et al., 2016; 2017).

107

108 In the context of dyslexia, motor imagery, as a process of exploration of sensorimotor representations,  
109 could provide insights on the quality of the perception-action coupling and especially on the functional  
110 link between language and sensorimotor representations. The present study aims specifically to explore  
111 the sensorimotor abilities and representations in young dyslexic adults. First, we hypothesized a higher  
112 percentage of sensorimotor disorders in the dyslexic group, with respect to the normo-reader group.  
113 Second, we expected a slow-down of performed actions in dyslexic subjects, enlarging the temporal  
114 adjustment deficit of phonological treatment to a global temporal sensorimotor deficit. Lastly, an  
115 impairment of internal model of articulatory and bodily actions was expected in dyslexic group and  
116 particularly in dyslexic subjects with sensorimotor disorders.

## 117 **Material and methods**

### 118 **Subjects**

119 A total of 110 post-graduate students, aged from 18 to 29 years, participated in this study, including 52  
120 participants with developmental dyslexia (DD: 21 men, 22 years  $\pm$  2.3 SD) and 58 normo-reader (NR:  
121 22 men, 22 years  $\pm$  2 SD). 105 were right-handed and 5 left-handed. The groups were similar in age,  
122 sex, and study field (natural and formal sciences, social sciences, arts and humanities). Within the  
123 sample of DD (63% women), 42.3% were enrolled in human and social science programs and 57.6% in  
124 formal and natural science programs. DD ranged in age from 18.1 to 29 years. Within the sample of NR  
125 (67% women), 41.3% were enrolled in human and social science programs and 58.6% in formal and  
126 natural science programs. NR ranged in age from 18.3 to 27 years. Participants were recruited from the  
127 university population through advertisements and information sessions at Aix-Marseille University.  
128 Participants gave their written informed consent prior to the experiment, which obtained the approval  
129 of the local ethics committee (CPP Sud Méditerranée 2) and was performed in accordance with the  
130 ethical standards of the Declaration of Helsinki.

131

132 All participants underwent neuropsychological assessment, including tests of intellectual abilities  
 133 (Raven's matrices; Raven, Raven & Court 1995) reading skills (Alouette test, Lefavrais, 2005, see  
 134 Cavalli et al., 2018), and phonological skills based on a pseudoword reading task (evaluated as an  
 135 accuracy score corresponding to the number of pseudowords correctly read in 2 minutes under time  
 136 pressure) reported in table 1. Participants with DD, in contrast to NR participants, met the DSM-V  
 137 diagnostic criteria for specific learning disorder with impairment in reading: (1) they showed difficulty  
 138 in mastering reading, as their accuracy and speed when reading were significantly lower, measured as a  
 139 performance for the Alouette reading text score <1,5 SD below the NR mean ; (2) they were diagnosed  
 140 for a reading problem by a speech therapist during childhood, and (3) they had no diagnosis of any  
 141 significant medical or social condition known to affect reading abilities and they did not have any sign  
 142 of intellectual disability (i.e., >25th percentile, Raven's matrices; Raven, Court, & Raven, 1995).  
 143 Inclusion criteria for all participants were the following: French as native language, the absence of visual  
 144 and auditive impairments, absence of neurological or chronic medical diseases, and an IQ scale within  
 145 the normal range (i.e., >25th percentile, Raven's matrices; Raven, Court, & Raven, 1995). All DD had  
 146 a formal diagnosis of dyslexia in elementary school or high school, and were required to be regularly  
 147 certified at the university office for disabilities.

148

149

Participant characteristics	NR (N = 58)		DD (N = 52)		Group differences	
	M	(SD)	M	(SD)	(W)	<i>p</i>
Age (years)	21.8	(2)	21.8	(2.3)	(0.02)	0.981
Non verbal IQ (Raven's matrices)	49.5	(4.8)	48	(5.2)	(1221)	0.167
Reading skills (Alouette test)	559	(93.3)	361	(73.13)	(111)	<0.001
Phonological skills	153.1	(39.69)	82.56	(23.72)	(140)	<0.001

(Pseudoword reading  
task)

---

150

151 **Table 1.** Means and standard deviations of characteristics of Normo-Readers subjects (NR) and subjects  
152 with developmental dyslexia (DD) with and without sensorimotor impairments (DDnoSM and DDSM,  
153 respectively).

## 154 **Experimental procedure**

### 155 **Movement assessment battery, M-ABC**

156 All participants completed the extended version of the M-ABC 2 (Henderson, Sugden, & Barnett, 2007).  
157 The French version (Marquet-Doléac et al., 2016) for the 3rd age band, which runs from 11 to 16 years  
158 and 11 months, was used for this study. The M-ABC is a reference test, extensively used in the  
159 international literature to assess motor deficits, particularly in population with learning disabilities. No  
160 test is yet, to our knowledge, available for young adults. Due to this lack of tool for the young adult  
161 population, the M-ABC has been regularly used, either in the total version or a subgroup of tasks, for  
162 an older population (see Cousins and Smyth 2003, Cantell et al., 2008, Borremans et al., 2009, Loras  
163 and Sigmundsson 2012). The M-ABC 2 consists of eight tasks, grouped into three categories: manual  
164 dexterity, aiming and catching, and balance. A score below or equal to the 5<sup>th</sup> percentile is considered  
165 to indicate a sensorimotor deficit. Assuming that the ceiling levels could be reached more easily due to  
166 the more advanced maturation of the motor system in our participants (young adults), the <5<sup>th</sup> percentile  
167 can be considered as a conservative cut off for motor impairments. Subjects with a score below the 5<sup>th</sup>  
168 percentile were selected as presenting a sensorimotor impairment.

169

### 170 **Mental imagery paradigm**

#### 171 **Data acquisition**

172 The mental imagery paradigm aimed to explore internal representations of action (see Wilson et al.,  
173 2004; Sinani et al., 2011). In our experiment, the subjects had to successively perform an action and

174 then imagine the same action they had just executed, in a series of five interlaced trials. The mental  
175 simulation of the motor tasks was clearly defined: subjects had to imagine themselves executing the  
176 action. In both cases, the subject self-records the duration of the action, both executed and imagined,  
177 using a stopwatch.

178

179 The actions of this study were chosen from the current daily life repertoire and combined sensorimotor  
180 and language features. Of the 8 tasks selected, some involved sensorimotor activities of the whole-body  
181 as normal gait, tandem gait, and sit-to-stand task, or focused on the upper limbs, such as grasping. Other  
182 tasks involved language activities with oral production, as repetition and reading aloud or without oral  
183 production, as a silent reading task, and a writing task. Motor ideation tasks on gait or sit-to-stand have  
184 been regularly used in healthy adult subjects (Chabeauti et al., 2012), children (Iosa et al., 2014) or  
185 elderly participants (Allali et al., 2013; Personnier et al., 2010) as well as in patient populations and  
186 remediation programs (Cho et al., 2012; Malouin et al., 2004). Writing (Guilbert et al., 2020) or grasping  
187 (Errante et al., 2019) were also studied in motor imagery protocols.

188 Moreover, to test the updating of internal representations, we also measured the duration of the imagined  
189 action after modification of the experimental environment, by moving away the target to be reached, for  
190 normal gait and grasping tasks. We speculated that an increase in the duration of the imagined action  
191 should reflect the updated process. After the imagined modified conditions, a block of five trials was  
192 then executed in the modified conditions and used as reference.

193

#### 194 **Data analysis**

195 For each subject, the mean duration (in seconds) and the standard deviation were calculated for each  
196 task and for each condition: the executed action (EA) and imagined action (IA). The variability in  
197 execution of the action was measured by calculating the coefficient of variation CoV  
198  $= \left( \frac{SD}{Mean\ Time} \right) \times 100$ . As excessive variability is a developmental feature that reflects task difficulty,  
199 indeed, Skoura and colleagues (2009) indicated a larger variability of execution durations in children  
200 with respect to adults, we used a variability index in addition to the execution time statistics.

201 In order to evaluate the efficiency of mental representation, we used a performance index (PI)  
202 corresponding to the absolute value of the executed minus imagined time divided by the executed time:  
203  $PI = \frac{|EA-IA|}{EA}$ . A similar performance index was previously used by several studies (Personnier et al.,  
204 (2010), Kalicinski et al., (2015), Fusco et al., (2019)), and allows us to include all tasks without  
205 considering the differences in duration due to their specific spatio-temporal features (eg. tandem gait  
206 and sit-to-stand task) and without taking into account the sign (+/-) of the difference between EA and  
207 EI. We interpret this PI as following: the closer the value of this index was to zero (small difference  
208 between EI and EA), the stronger the simulation of the performance.”

209

## 210 **Statistical analyses**

211 The first analysis was performed on the two groups, DD (n=52) versus NR (n=58), to evaluate the  
212 occurrence of sensorimotor impairment in both groups, based on the M-ABC. The dependent variables  
213 -i.e. duration of EA and IA, coefficient of variation (CoV), and PI- didn't displayed acceptable normal  
214 distributions. Accordingly, the statistical analyses were performed using nonparametric test and group  
215 data were reported as median and interquartile range. Between-group difference in the duration and CoV  
216 of the EA was assessed using global (tasks pooled) or task-by-task Mann-Whitney test and Kruskal-  
217 Wallis tests (whether on two or three groups). Isochrony was investigated using Wilcoxon matched-  
218 paired signed rank tests. The p-value of these tests was then Bonferroni corrected. The performance  
219 indexes (PI) were compared between groups by a global (tasks pooled) Mann-Whitney test on the two  
220 groups and a global (tasks pooled) Kruskal-Wallis test on the subgroup. No difference between the two  
221 PIs meant a good update of the internal representations of action. Task-by-task Mann-Whitney test and  
222 Kruskal-Wallis tests were also performed. The updating tasks on simple gait and grasping was analyzed  
223 using a global (tasks pooled) Mann-Whitney test Kruskal-Wallis test.

224 Differences with a *p* value < 0.05 were considered to be statistically significant.

225

## 226 **Results**

227 **Sensorimotor evaluation**

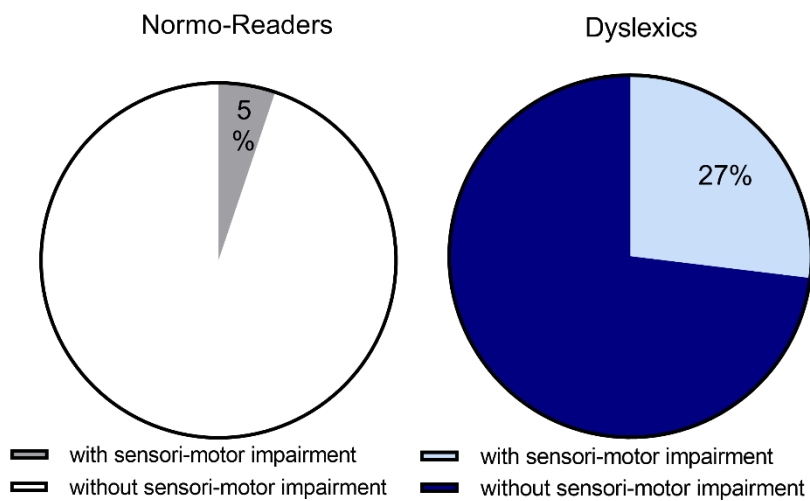
228 **Associated motor impairment**

229 Subjects that scored below the 5<sup>th</sup> percentile represented 5% of the NR group and 27% of the DD group.

230 Sensorimotor impairment prevalence for both groups is presented in Figure 1. DD subjects with

231 sensorimotor impairment were referred as *DDSM*, as opposed to DD subjects without sensorimotor

232 impairment referred as *DDnoSM*.



233  
234 **Fig. 1** : Prevalence of sensorimotor impairments in percentage in normo-readers subjects (left part)  
235 and dyslexics subjects (right part).

236  
237 **Temporal parameters of executed actions (EA) - Mean and CoV**

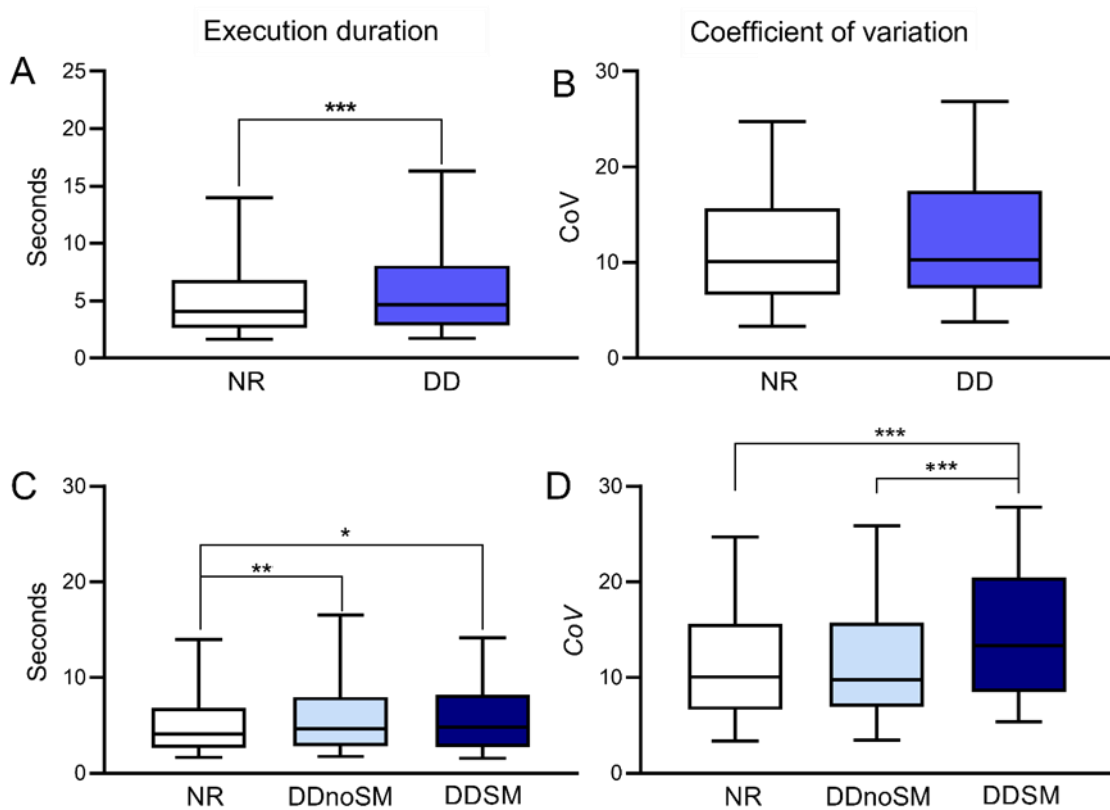
238 Global EA durations and CoV are summarized in Figure 2.

239 Concerning the duration of EA, the global Mann-Whitney test on the two groups revealed a significant  
240 difference between NR (mdn = 3.88, 2.56 – 5.74) and DD (mdn = 4.44, 2.75 – 7.50) ( $U = 67425$ ;  $p =$   
241  $0.0006$ ). NRs showed shorter executed duration than DD. Task by task Mann-Whitney test revealed a  
242 significant difference between NR and DD on the tandem ( $p=0.016$ ), repetition ( $p=0.032$ ), reading aloud  
243 ( $p<0.0001$ ), silent reading ( $p<0.0001$ ), and writing ( $p=0.036$ ) task.

244 If we consider the subgroup level, the global Kruskal-Wallis test revealed a significant effect of Group  
245 ( $H(2) = 11.95, p = 0.0025$ ). Post-hoc analyses revealed that executed durations were significantly shorter  
246 between NRs and the two groups of DDs (DDnoSM:  $p = 0.008$ , DDSM:  $p = 0.037$ ), but no significant  
247 difference emerged between DDnoSM and DDSM. Task by task Mann-Whitney test on the subgroups  
248 demonstrated that NRs were significantly faster than both dyslexic groups in reading tasks (reading  
249 aloud:  $p < 0.001$  for both comparisons; silent reading:  $p < 0.001$  for both comparisons) and faster than  
250 DDnoSM in the tandem gait tasks ( $p = 0.043$ ).

251

252 Concerning the CoV, the global Mann-Whitney test on the two groups revealed no effect of the Group.  
253 If we consider the subgroup level, the Kruskal-Wallis test revealed a significant effect of Group ( $H(2)$   
254  $= 17.53, p = 0.0002$ ). Post-hoc analyses revealed that CoVs were significantly larger in DDSM,  
255 compared both with NRs ( $p = 0.0002$ ) and DDnoSM ( $p = 0.0003$ ), but no significant difference emerged  
256 between DDnoSM and NRs. Task by task Mann-Whitney test on the subgroups demonstrated that NRs  
257 CoV were significantly smaller than DDSMs in the repetition ( $p = 0.0023$ ) and writing ( $p = 0.03$ ) tasks.  
258 Thus, both groups of dyslexics were found to have significantly longer action duration than NRs.  
259 Furthermore, a higher variability seems to be specific to DDSM, concerning executed action duration.



260

261

262 **Fig. 2:** Medians and interquartile ranges of temporal parameters of executed action in the normo-  
 263 readers group (NR), dyslexics subjects (DD), and dyslexics subjects with sensorimotor impairments  
 264 (DDSM) and dyslexic subjects without sensorimotor impairments (DDnoSM). Left part (A and C):  
 265 Execution duration in seconds and right part (B and D): coefficient of variation. \*\*\*  $p < 0.001$ ; \*\*  
 266  $p < 0.01$  and \* $p < 0.05$ .

## 267 Motor imagery

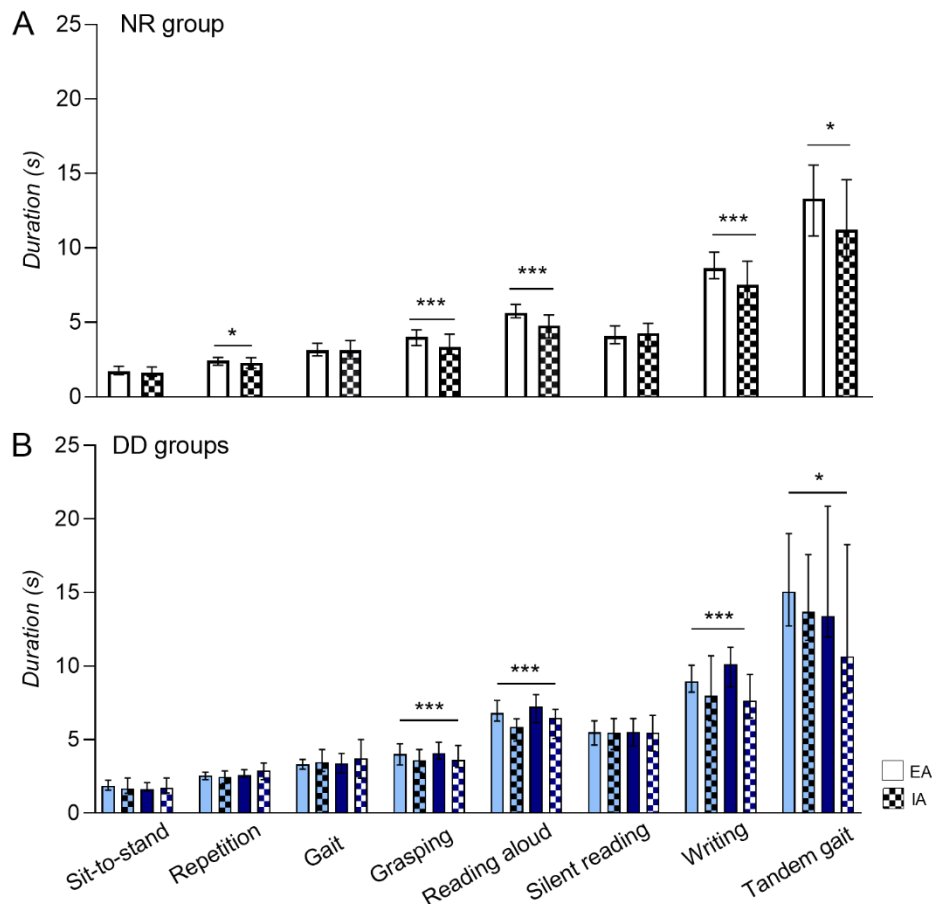
### 268 Temporal analysis of executed versus imagined actions – Isochrony

269 Isochrony by groups is summarized in Figure 3.

270 A. NR: Concerning the mean duration time, the Wilcoxon matched-paired signed rank test,  
 271 revealed a significant difference between EA and IA duration for the repetition ( $W = -508$ ,  $p = 0.0296$ ),

272 reading aloud ( $W = -1471, p < 0.001$ ), tandem gait ( $W = -712, p = 0.04$ ), writing ( $W = -581, p < 0.001$ ) and  
 273 grasping task ( $W = -1024, p < 0.001$ ).

274 B. DD: Concerning the mean duration time, the Wilcoxon matched-paired signed rank test,  
 275 revealed a significant difference between EA and IA duration for the reading aloud ( $W = -948, p < 0.001$ ),  
 276 tandem gait ( $W = -660, p = 0.0176$ ), writing ( $W = -804, p < 0.001$ ) and grasping task ( $W = -886, p < 0.001$ ).  
 277



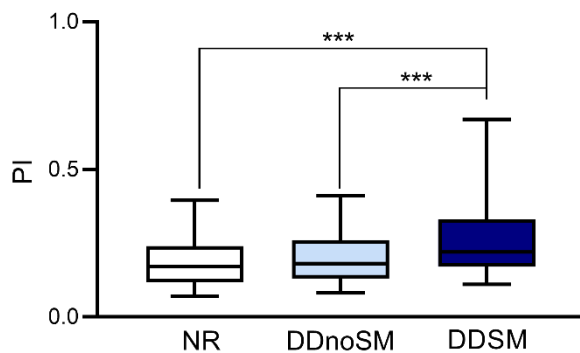
278  
 279  
 280 **Fig. 3:** Medians and interquartile ranges of durations of executed actions (EA, full boxes) and imagined  
 281 actions (IA, checkerboard boxes) in all tasks for the normo-readers group (White, NR), dyslexics  
 282 subjects without sensorimotor impairments (DDnoSM, light blue), and dyslexics subjects with  
 283 sensorimotor impairments (DDSM, dark blue). \*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$  and \*  $p < 0.05$ .  
 284

285 **Efficiency of mental imagery - performance index (PI)**

286 The performance indexes are presented in figure 4.

287 Concerning the PI, the global Mann-Whitney test on the two groups revealed a significant difference  
288 between NRs (mdn = 0.17, 0.11-0.23) and DDs (mdn = 0.19, 0.13-0.27) ( $U = 76463$ ,  $p = 0.0008$ ). PI in  
289 NR is stronger than in DD, as attested by a lower score. Task by task Mann-Whitney test on the  
290 subgroups demonstrated that NRs performed better in the sit-to-stand ( $p=0.033$ ) and silent reading  
291 ( $p=0.029$ ) task.

292 If we consider the subgroup level, the global Kruskal-Wallis test revealed a significant effect of Group  
293 ( $H(2) = 25.56$ ,  $p < 0.0001$ ). Post-hoc analyses revealed that DDSM scores were significantly worse than  
294 those of NRs ( $p < 0.0001$ ) and DDnoSMs ( $p = 0.0004$ ), while DDnoSMs and NRs did not differ. Task by  
295 task Mann-Whitney test on the subgroups demonstrated that NRs performed better in the sit-to-stand  
296 ( $p=0.02$ ) and repetition ( $p=0.01$ ) tasks. Thus, DDSM revealed poorer skills performances in mental  
297 imagery than in NR and DDnoSM.

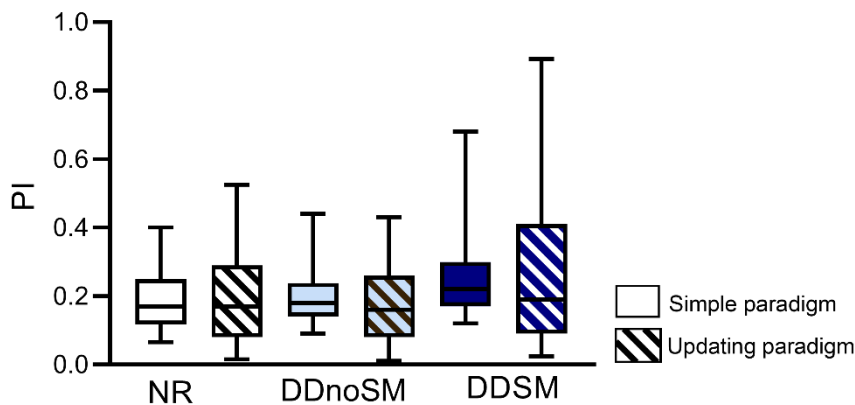


298  
299 **Fig. 4:** Medians and interquartile ranges of global performance index (PI) for the normo-readers group  
300 (white, NR), dyslexics subjects without sensorimotor impairments (DDnoSM, light blue) and  
301 dyslexics subjects with sensorimotor impairments (DDSM, dark blue). \*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$  and  
302 \* $p < 0.05$ .

303

304 **Efficiency of updating internal model tasks - PI**

305 The PI between the simple versus updating paradigm in both PI tasks (i.e., locomotion and grasping), is  
306 presented in the Figure 5. The global Mann-Whitney test on the two groups and the Kruskal-Wallis test  
307 on the subgroup revealed no group effect on the updating paradigm performance, reflecting similar  
308 updating of representation in NRs and in DDs. Thus, the updating of representations was similar in DDs  
309 with or without sensorimotor impairments, as compared to NRs.



310

311 **Fig.5:** Medians and interquartile ranges of performance index (PI) in the simple paradigm (full box)  
312 and updating paradigm (hatched box) for the normo-readers group (white, NR), dyslexics subjects  
313 without sensorimotor impairments (DDnoSM, light blue), and dyslexics subjects with sensorimotor  
314 impairments (DDSM, dark blue). With \*\*\*  $p < 0.001$ .

315

### 316 **Correlations between reading skills and motor imagery**

317 Concerning motor imagery performances, no significant correlation was observed between the reading  
318 efficiency score on the Alouette reading test and mental imagery performances (PI) whether in the DD  
319 or NR group.

320

## 321 **Discussion**

322 The first outcome of the present study is the presence of a sensorimotor impairments in 27% of the  
323 young adult dyslexics, as revealed by the M-ABC2. This confirmed previous studies over the past 30

324 years (Cignetti et al., 2018; Ramus et al., 2003a and b) and raises the question of a sensorimotor  
325 impairment profile beyond the typical consensual phonological deficit. The second main result emerging  
326 from this study is that motor imagery, as a process of exploration of sensorimotor representations, was  
327 impacted only in the specific dyslexic subgroup with sensorimotor impairments. This highlights the  
328 importance of the quality of the perception-action coupling to establish the functional link between  
329 language and sensorimotor representations, which is indispensable for reading.

### 330 **Sensorimotor comorbidity confirmed in young dyslexic adults**

331 From a large cohort of well-characterized young dyslexic adults matched for age, sex, education level,  
332 and non-verbal IQ, we confirmed a larger percentage of sensorimotor impairment of the young adult  
333 dyslexics (at least 27%), as opposed to the normo-reader group (at least 5%), whose sensorimotor  
334 impairment percentage is consistent with previous developmental studies reporting in global population  
335 (APA, 2013, Zoia et al., 2006).

336 In the past, from the assumption of a single and sufficient etiology of dyslexia, sensorimotor  
337 impairments were not systematically evaluated. Nowadays, considering the polymorph dyslexic profiles  
338 (Pennington 2006; Van Bergen et al., 2014), the impact of the sensorimotor comorbidity risks in dyslexia  
339 deserves to be re-visited. To evaluate sensorimotor impairments, we chosen the M-ABC 2 test, an  
340 internationally reference for Developmental Coordination Disorder (Henderson, Sugden, & Barnett,  
341 2007), extended to 17 years of age and adapted to young adults with small adaptations of the daily  
342 activities questionnaire, according to the recommendations of the European Academy of Childhood  
343 Disability, that reports a lack of standardized assessments for adults with DCD at present (Blank et al.,  
344 2019). Although we reported a significant occurrence of SM impairment in DD (27%), the percentage  
345 could be increased if this first evaluation was completed by an exhaustive postural study focused on  
346 balance control, sensory reweighting, and motor prediction, which are mainly reported as impacted in  
347 DCD populations (cf. recent reviews Adams et al., 2014, Wilson et al., 2013; 2017).

348 **Motor slowdown and execution variability reflecting motor difficulty persist in**  
349 **dyslexic adults**

350 Accordingly with our expectations, the slowdown, classically observed in reading or spelling in dyslexia  
351 seemed to be confirmed in some tasks in our study. Beyond reading skills, tasks mainly involving  
352 sensorimotor activities of the whole body, such as tandem gait, were also executed slowly by dyslexic  
353 adults. These results seem to expand the problem of temporal adjustment of phonemic control to a global  
354 temporal motor deficit. Moreover, this slowdown was observed in both subgroups of dyslexic adults,  
355 with or without sensorimotor impairment. In the same vein, it deserves to be noted that Goswami, as  
356 soon as 2011, proposed that temporal sampling of speech by neuroelectric oscillations that encode  
357 incoming information at different frequencies could explain the perceptual and phonological difficulties  
358 found in individuals with dyslexia.

359 In typical sensorimotor development, the slowing of motor performances is the first adaptive strategy  
360 in response to increasing difficulties that need to be overcome (Assaiante and Amblard, 1995). Similar  
361 slowness accompanies motor performance in adults with developmental coordination disorder (DCD)  
362 (Cousins and Smyth, 2003). A recent study about action representation deficits in adolescents with  
363 developmental dyslexia (Van de Walle de Ghelcke et al., 2020) also reported slowness of both actual  
364 and mental movements. These authors interpreted this novel result as an alteration in cognitive  
365 mechanisms, responsible for the mental sensorimotor representation in addition to those observed in  
366 movement execution. Currently we report similar results in young dyslexic adults engaged in mental  
367 representation of various current daily life actions.

368 Excessive variability is another developmental feature that reflects task difficulty. Indeed, Skoura and  
369 colleagues (2009) indicated a larger variability of execution durations in children with respect to adults.  
370 In contrast with slowness, only the dyslexic subgroup with sensorimotor impairment (DDSM) showed  
371 an increased variability in execution durations, with respect to both dyslexics without sensorimotor  
372 impairment and the normo-reader group. High levels of variability in motor and locomotor parameters  
373 is indicative of poor motor control (Moe-Nilssen & Helbostad, 2005) and is typical of sensorimotor

374 disorders such as in DCD children (Licari and Reynolds, 2017; Smits-Engelsman et al., 2012; Wilmut  
375 et al., 2017). Thus, the variability observed in the young DDSMI adults may be understood as a delayed  
376 maturation of motor control, as found for example in DCDs.

377

378 **Isochrony between overt and covert actions is present in dyslexic adults and**  
379 **normo-readers**

380 Based on previous studies on motor imagery (Papaxanthis et al., 2002; Skoura et al., 2009), we were  
381 firstly interested in confirming the isochrony principle in various daily tasks combining multiple  
382 cognitive and motor constraints, in dyslexic adults and normo-readers. Indeed, temporal similarities  
383 were reported in half of the tasks in adult normo-readers. As similar increased durations of actual and  
384 mental movements were observed in dyslexic adults, the isochrony principle was also confirmed in this  
385 group engaged in silent reading, postural, and locomotor tasks.

386 Imagining the action previously executed, as in our protocol, involved the cooperation of two main  
387 sources of sensory information: vision and proprioception that increased the vividness of the  
388 representation into a unified internal representation of the body (Assaiante et al., 2014). Indeed, many  
389 studies have revealed an impact of sensory information on the mental imagery process (Guilbert et al.,  
390 2018; Naito et al., 2002; Sirigu and Duhamel, 2001; Vargas 2004). Similarly, it was reported that motor  
391 imagery is more easily performed when actual posture and imagined movement are congruent (Guilbert  
392 et al., 2020; Ionta et al., 2007; Sirigu and Duhamel, 2001; Vargas 2004), as proposed in our present  
393 study.

394 **Internal representations of action impacted only in dyslexic with sensorimotor**  
395 **impairments**

396 Based on a performance index of motor imagery, we reported that only dyslexic adults with  
397 sensorimotor impairments showed a lower efficiency of mental imagery. Similar deficits were already  
398 observed in one of the few studies focusing adults with probable DCD performing a mental hand rotation  
399 task (Hyde et al., 2014). Moreover, Van de Walle de Ghelcke and colleagues (2020) claimed recently  
400 that the process of action representation is also impacted in adolescents with developmental dyslexia.  
401 Unfortunately, no sensorimotor evaluation was performed in these adolescents in order to examine the  
402 impact of comorbidity in the sensorimotor perspective of dyslexia. Nevertheless, recent developmental  
403 studies highlight a long maturational process of the cortical correlates underlying motor anticipation,  
404 from late childhood to adulthood (Cignetti et al., 2018; Fortin et al., 2021) and the development of  
405 internal representations (Cignetti et al., 2016; Fontan et al., 2017), with a protracted development of the  
406 proprioceptive brain network during and beyond adolescence. Thus, because adolescence is a transient  
407 period in typical and atypical development and neurodevelopment, we speculate that sensorimotor  
408 contribution would be larger in developmental dyslexia during this period (Assaiante et al., 2014, 2019).  
409 In this context, the 'internal modeling deficit' reported in DCD, seems to be shared by various  
410 neurodevelopmental learning disorders and supports the sensorimotor perspective of dyslexia, with a  
411 flexible contribution according to the developmental periods.

### 412 **Efficiency of updating internal model is not impacted in dyslexic adults**

413 Because of the rapid updating of an internal model is the main difficulty in motor learning, as frequently  
414 reported in DCD, we hypothesized that we would find such difficulties in the dyslexic subgroup,  
415 particularly those with sensorimotor impairments. By contrast with our hypothesis, we did not observe  
416 updating deficits in either dyslexic group. As in normo-readers, dyslexic adults showed immediate  
417 duration adaptation in imagined tasks, in response to distance increased, reflecting that the efficiency of  
418 mental imagery is not impacted in the updating paradigm. Nevertheless, our updating paradigm was  
419 based on easy and familiar tasks of daily life (walking and grasping). A more complex task, out of  
420 ecological context, like a mental hand rotation task used by Hyde and collaborators (2014), or sequence  
421 learning used by Biotteau and colleagues (2015), could induce some difficulties.

422

## 423 **Conclusion**

424 The original aim of the current study was to determine the impact of comorbidity risks in the dyslexia  
425 deficits by integrating phonological and sensorimotor hypotheses of dyslexia in a unified framework.  
426 The present study highlighted a larger percentage of sensorimotor impairments of young adult dyslexics  
427 (27%), as opposed to the normo-reader group (5%), and an impaired internal representation of action  
428 was found only in the subgroup of comorbid dyslexic adults. Mental action representation could be a  
429 cerebral mechanism commonly impaired in dyslexia and DCD and supports the sensorimotor  
430 perspective of a dyslexic's profile. However, the present study does not allow us to determine whether  
431 sensorimotor representation deficits are inherent to a particular sub-group of dyslexic adults or inherent  
432 to DCD, and thus are exacerbated in the case of comorbidity, like in our sample. To address these  
433 different issues, future research performed in dyslexic, DCD, and comorbid subjects is required. In  
434 addition, an effort should be made to increase the size of the comorbid group (14 subjects), probably by  
435 direct sensorimotor deficits inclusion criteria. This would allow the exploration of the underlying neural  
436 basis of the functional links between language and sensorimotor representations and whether these  
437 features are supported by cerebral particularities in networks devoted to internal representation of action  
438 and learning process such as fronto-parietal, cingulo-opercular, somato-motor, and cerebellar-cortical  
439 networks (Cignetti et al., 2018; 2020).

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## 445 **Declaration of Conflicting Interests**

446 The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or  
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