



HAL
open science

A sensorimotor representation impairment in dyslexic adults: A specific profile of comorbidity

Rebecca Marchetti, Marianne Vaugoyeau, Pascale Colé, Christine Assaiante

► **To cite this version:**

Rebecca Marchetti, Marianne Vaugoyeau, Pascale Colé, Christine Assaiante. A sensorimotor representation impairment in dyslexic adults: A specific profile of comorbidity. *Neuropsychologia*, 2022, 165, pp.108134. 10.1016/j.neuropsychologia.2021.108134 . hal-03869835

HAL Id: hal-03869835

<https://hal.science/hal-03869835v1>

Submitted on 16 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

3

Rebecca Marchetti^{a,b,c}, Marianne Vaugoyeau^{a,c}, Pascale Colé^{b,c}, Christine Assaiante^{a,c}

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 (RM)

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 5th 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 <5th percentile
167 can be considered as a conservative cut off for motor impairments. Subjects with a score below the 5th
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**

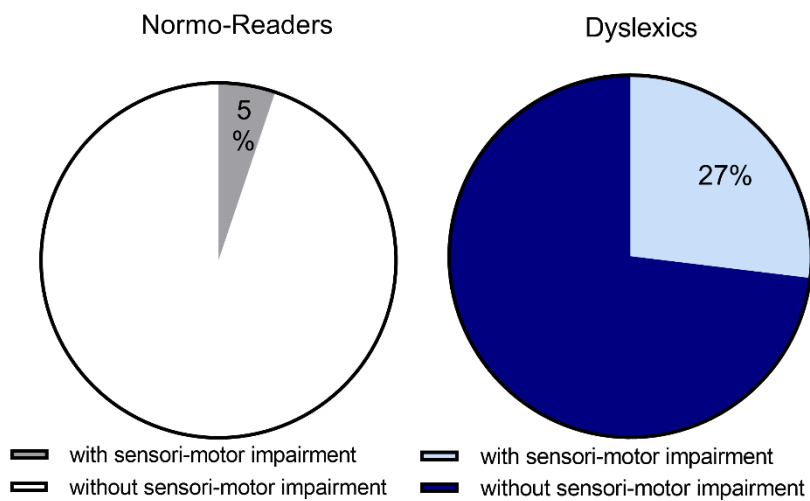
228 **Associated motor impairment**

229 Subjects that scored below the 5th 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**

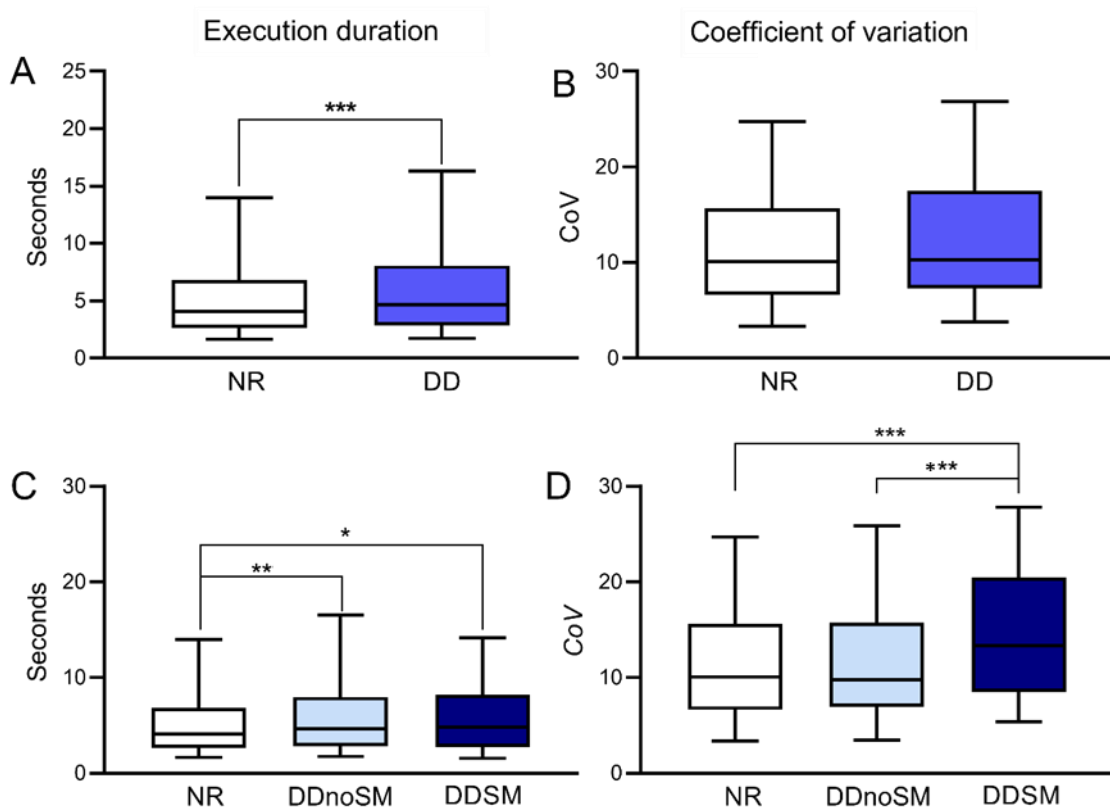
238 Global EA durations and CoV are summarized in Figure 2.

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

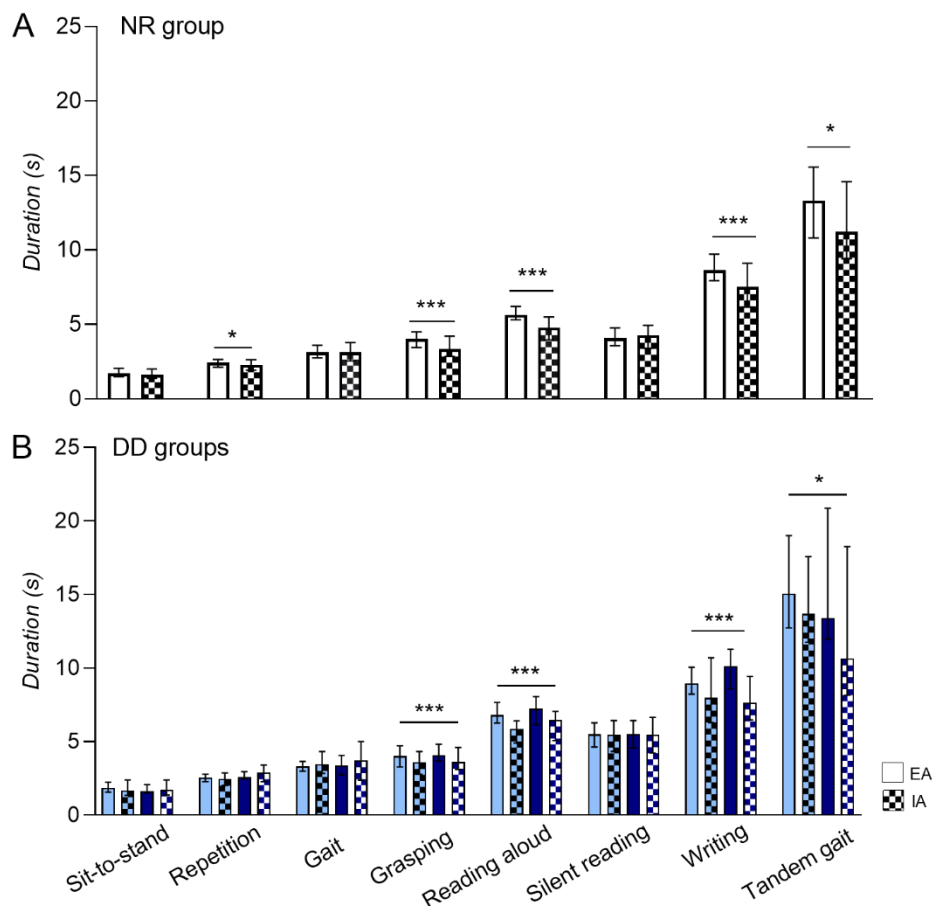
268 Temporal analysis of executed versus imagined actions – Isochrony

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



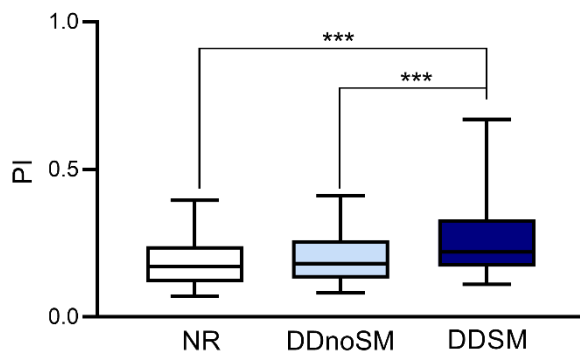
278
 279
 280 **Fig. 3:** Medians and interquartile ranges of durations of executed actions (EA, full boxes) and imagined
 281 actions (IA, checkerboard boxes) in all tasks for the normo-readers group (White, NR), dyslexics
 282 subjects without sensorimotor impairments (DDnoSM, light blue), and dyslexics 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.

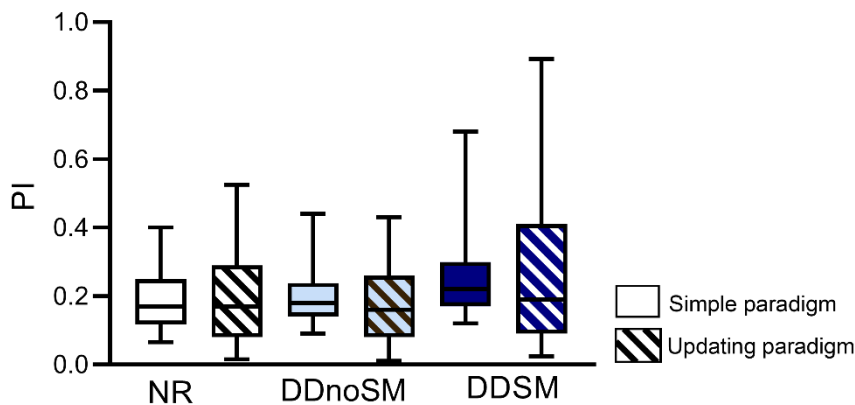


298
299 **Fig. 4:** Medians and interquartile ranges of global performance index (PI) for the normo-readers group
300 (white, NR), dyslexics subjects without sensorimotor impairments (DDnoSM, light blue) and
301 dyslexics subjects with sensorimotor impairments (DDSM, dark blue). *** $p < 0.001$; ** $p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

440 **Acknowledgment**

441 We gratefully acknowledge all the participants of this study. This work was supported by a grant from
442 the Fédération 3C, Aix Marseille Univ, CNRS, in Marseille, France. We wish to thank Rochelle
443 Ackerley for revising the English version of the manuscript and Serge Pinto for critically reviewing the
444 manuscript.

445 **Declaration of Conflicting Interests**

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

448 **References**

449 1. Adams ILJ, Lust JM, Wilson PH, Steenbergen B. Testing predictive control of movement
450 in children with developmental coordination disorder using converging operations. *Br J*
451 *Psychol.* Febr 2017;108(1):73-90.

452

453 2. Adams ILJ, Lust JM, Wilson PH, Steenbergen B. Compromised motor control in children
454 with DCD: A deficit in the internal model? A systematic review. *Neuroscience &*
455 *Biobehavioral Reviews.* Nov 2014;47:225-44.

456

457 3. Allali, G., van der Meulen, M., Beauchet, O., Rieger, S. W., Vuilleumier, P., & Assal, F.
458 The Neural Basis of Age-Related Changes in Motor Imagery of Gait : An fMRI Study. *The*
459 *Journals of Gerontology: Series A*, 69(11), 1389-1398. 2013;

460 <https://doi.org/10.1093/gerona/glt207>

461

462 4. Alexander-Passe N. How dyslexic teenagers cope: an investigation of self-esteem, coping
463 and depression. *Dyslexia.* Nov 2006;12(4):256-75.

464

465 5. American Psychiatric Association. Diagnostic and statistical manual of mental disorders:
466 DSM-5. London American Psychiatric Publishing. 2013;

467

- 468 6. Assaiante C, Amblard B. An ontogenetic model for the sensorimotor organization of
469 balance control in humans. *Human Movement Science*. June 1995;14(1):13-43.
470
- 471 7. Assaiante C, Barlaam F, Cignetti F, Vaugoyeau M. Body schema building during
472 childhood and adolescence: A neurosensory approach. *Neurophysiologie Clinique/Clinical*
473 *Neurophysiology*. Janu 2014;44(1):3-12.
474
- 475 8. Assaiante, Christine, Vaugoyeau M, Cignetti, Fabien. Contrôle anticipé chez des enfants de
476 8 à 12 ans avec des troubles des apprentissages : importance de la comorbidité.
477 *Neurophysiologie Clinique*. 2019;
478
- 479 9. Barlaam F, Fortin C, Vaugoyeau M, Schmitz C, Assaiante C. Development of action
480 representation during adolescence as assessed from anticipatory control in a bimanual load-
481 lifting task. *Neuroscience*. Sept 2012;221:56-68.
482 9.
- 483 10. Biotteau M, Chaix Y, Albaret J-M. Procedural learning and automatization process in
484 children with developmental coordination disorder and/or developmental dyslexia. *Human*
485 *Movement Science*. Oct 2015;43:78-89.
486
- 487 11. Biotteau M, Chaix Y, Albaret J-M. What Do We Really Know About Motor Learning in
488 Children with Developmental Coordination Disorder? *Curr Dev Disord Rep*. June
489 2016;3(2):152-60.
490
- 491 12. Biotteau, M., Albaret, J.-M., Lelong, S., & Chaix, Y. Neuropsychological status of French
492 children with developmental dyslexia and/or developmental coordination disorder : Are both

493 necessarily worse than one? Child Neuropsychology. 2017 ;23(4), 422-441.

494 <https://doi.org/10.1080/09297049.2015.1127339>

495

496 13. Blank R, Barnett AL, Cairney J, Green D, Kirby A, Polatajko H, et al. International
497 clinical practice recommendations on the definition, diagnosis, assessment, intervention, and
498 psychosocial aspects of developmental coordination disorder. Dev Med Child Neurol. March
499 2019;61(3):242-85.

500

501 14. Borremans E, Rintala P, McCubbin JA. Motor skills of young adults with asperger
502 syndrome: a comparative study. Eujapa. 31 mars 2009;2(1):21-33.

503

504 15. Brown T. Movement Assessment Battery for Children: 2nd Edition (MABC-2). In:
505 Volkmar FR, éditeur. Encyclopedia of Autism Spectrum Disorders. New York, NY: Springer
506 New York; 2018. p. 1-20.

507

508 16. Burden, R. Is dyslexia necessarily associated with negative feelings of self-worth? A
509 review and implication for future research. Dyslexia. 2008;

510

511 17. Cantell M, Crawford SG, (Tish) Doyle-Baker PK. Physical fitness and health indices in
512 children, adolescents and adults with high or low motor competence. Human Movement
513 Science. Apr 2008;27(2):344-62.

514

515 18. Cantell MH, Smyth MM, Ahonen TP. Two distinct pathways for developmental
516 coordination disorder: Persistence and resolution. Human Movement Science. Nov
517 2003;22(4-5):413-31.

518

519 19. Cavalli E, Colé P, Leloup G, Poracchia-George F, Sprenger-Charolles L, El Ahmadi A.

520 Screening for Dyslexia in French-Speaking University Students: An Evaluation of the

521 Detection Accuracy of the *Alouette* Test. *J Learn Disabil.* may 2018;51(3):268-82.

522

523 20. Chabeauti, P. Y., Assaiante, C., & Vaugoyeau, M. Extreme short-term environmental

524 constraints do not update internal models of action as assessed from motor imagery in adults.

525 *Neuroscience.* 2012; 222, 69-74. <https://doi.org/10.1016/j.neuroscience.2012.07.002>

526

527 21. Cho, H., Kim, J., & Lee, G.-C. (2012). Effects of motor imagery training on balance and

528 gait abilities in post-stroke patients : A randomized controlled trial. *Clinical Rehabilitation.*

529 2013 ; 27(8), 675-680. <https://doi.org/10.1177/0269215512464702>

530

531 22. Cignetti F, Chabeauti P-Y, Sveistrup H, Vaugoyeau M, Assaiante C. Updating process of

532 internal models of action as assessed from motor and postural strategies in children.

533 *Neuroscience.* March 2013;233:127-38.

534

535 23. Cignetti F, Fontan A, Menant J, Nazarian B, Anton J-L, Vaugoyeau M, et al. Protracted

536 Development of the Proprioceptive Brain Network During and Beyond Adolescence. *Cereb*

537 *Cortex.* 4 janu 2016.

538

539 24. Cignetti F, Nemmi F, Vaugoyeau M, Girard N, Albaret J-M, Chaix Y, et al. Intrinsic

540 Cortico-Subcortical Functional Connectivity in Developmental Dyslexia and Developmental

541 Coordination Disorder. *Cerebral Cortex Communications.* 5 aug 2020;1.

542

- 543 25. Cignetti F, Vaugoyeau M, Fontan A, Jover M, Livet M-O, Hugonenq C, et al.
544 Feedforward motor control in developmental dyslexia and developmental coordination
545 disorder: Does comorbidity matter? *Res Dev Disabil.* may 2018;76:25-34.
546
- 547 26. Cousins M, Smyth MM. Developmental coordination impairments in adulthood. *Human*
548 *Movement Science.* Nov 2003;22(4-5):433-59.
549
- 550 27. Davis TE, Nida RE, Zlomke KR, Nebel-Schwalm MS. Health-Related Quality of Life in
551 College Undergraduates with Learning Disabilities: The Mediation Roles of Anxiety and
552 Sadness. *J Psychopathol Behav Assess.* 24 oct 2008;31(3):228.
553
- 554 28. De La Haye F, Gombert J-E, Riviere J-P, Rocher T. Les évaluations en lecture dans le
555 cadre de la journée d'appel de préparation à la défense: 2010. 2011;8.
556
- 557 29. Decety J. Neural mechanisms subserving the perception of human actions. *Trends in*
558 *Cognitive Sciences.* 1 may 1999;3(5):172-8.
559
- 560 30. Decety, J., Grèzes, J. The power of simulation: Imaging one's own and other's behavior.
561 *Brain Research.* 2006;
562
- 563 31. Deconinck FJA, Spitaels L, Fias W, Lenoir M. Is developmental coordination disorder a
564 motor imagery deficit? *Journal of Clinical and Experimental Neuropsychology.* 27 July
565 2009;31(6):720-30.
566

- 567 32. Errante, A., Bozzetti, F., Sghedoni, S., Bressi, B., Costi, S., Crisi, G., Ferrari, A., &
568 Fogassi, L. Explicit Motor Imagery for Grasping Actions in Children With Spastic Unilateral
569 Cerebral Palsy. *Frontiers in Neurology*. 2019; *10*, 837.
570 <https://doi.org/10.3389/fneur.2019.00837>
571
- 572 33. Fadiga L, Fogassi L, Pavesi G, Rizzolatti G. Motor facilitation during action observation:
573 a magnetic stimulation study. *Journal of Neurophysiology*. 1 June 1995;73(6):2608-11.
574
- 575 34. Flanagan JR, Wing AM. The Role of Internal Models in Motion Planning and Control:
576 Evidence from Grip Force Adjustments during Movements of Hand-Held Loads. *J Neurosci*.
577 15 fébr 1997;17(4):1519-28.
578
- 579 35. Fontan A, Cignetti F, Nazarian B, Anton J-L, Vaugoyeau M, Assaiante C. How does the
580 body representation system develop in the human brain? *Developmental Cognitive*
581 *Neuroscience*. Apr 2017;24:118-28.
582
- 583 36. Fortin, C., Barlaam, F., Vaugoyeau, M., Assaiante, C. Neurodevelopment of posture-
584 movement coordination from late childhood to adulthood as assessed from bimanual load-
585 lofting task: an event-related potential study. *Neuroscience*. 2021;
586
- 587 37. Fuelscher I, Williams J, Enticott PG, Hyde C. Reduced motor imagery efficiency is
588 associated with online control difficulties in children with probable developmental
589 coordination disorder. *Research in Developmental Disabilities*. Oct 2015;45-46:239-52.
590

- 591 38. Furnes, B, Norman, E. Three forms of metacognition in normally developing readers and
592 readers with dyslexia. *Dyslexia*. 2015;
593
- 594 39. Fusco, A., Iasevoli, L., Iosa, M., Gallotta, M. C., Padua, L., Tucci, L., Antonucci, G.,
595 Baldari, C., & Guidetti, L. Dynamic motor imagery mentally simulates uncommon real
596 locomotion better than static motor imagery both in young adults and elderly. *PLOS ONE*.
597 2019; 14(6), e0218378. <https://doi.org/10.1371/journal.pone.0218378>
598
- 599 40. Goswami, U. A temporal sampling framework for developmental dyslexia. *Trends in*
600 *Cognitive Sciences*. 2011; 15(1), 3-10. <https://doi.org/10.1016/j.tics.2010.10.001>
601
- 602 41. Gabbard C, Bobbio T. The Inability To Mentally Represent Action May Be Associated
603 With Performance Deficits in Children With Developmental Coordination Disorder.
604 *International Journal of Neuroscience*. Janu 2011;121(3):113-20.
605
- 606 42. Grabski K, Sato M. Adaptive phonemic coding in the listening and speaking brain.
607 *Neuropsychologia*. Janu 2020;136:107267.
608
- 609 43. Guilbert J, Jouen F, Molina M. Motor imagery development and proprioceptive
610 integration: Which sensory reweighting during childhood? *Journal of Experimental Child*
611 *Psychology*. Febr 2018;166:621-34.
612
- 613 44. Guilbert J, Fernandez J, Molina M, Morin M-F, Alamargot D. Imagining handwriting
614 movements in a usual or unusual position: effect of posture congruency on visual and
615 kinesthetic motor imagery. *Psychological Research*. 2 aug 2020.

616

617 45. Guilbert, J., Fernandez, J., Molina, M., Morin, M.-F., & Alamargot, D. Imagining
618 handwriting movements in a usual or unusual position : Effect of posture congruency on
619 visual and kinesthetic motor imagery. *Psychological Research*. 2021; 85(6), 2237-2247.
620 <https://doi.org/10.1007/s00426-020-01399-w>

621

622 46. Guillot A, Di Rienzo F, MacIntyre T, Moran A, Collet C. Imagining is Not Doing but
623 Involves Specific Motor Commands: A Review of Experimental Data Related to Motor
624 Inhibition. *Front Hum Neurosci*. 2012;6.

625

626 47. Habib M. The neurological basis of developmental dyslexia: An overview and working
627 hypothesis. *Brain*. 1 déc 2000;123(12):2373-99.

628

629 48. Hardwick, R. M., Caspers, S., Eickhoff, S. B., & Swinnen, S. P. Neural correlates of
630 action : Comparing meta-analyses of imagery, observation, and execution. *Neuroscience &*
631 *Biobehavioral Reviews*. 2018; 94, 31-44. <https://doi.org/10.1016/j.neubiorev.2018.08.003>

632

633 49. Henderson, S. E., Sugden, D. A., Barnett, A. L. Movement assessment battery for
634 children. London : Harcourt Assessment. 2007;26.

635

636 50. Héту, S., Grégoire, M., Saimpont, A., Coll, M.-P., Eugène, F., Michon, P.-E., & Jackson,
637 P. L. The neural network of motor imagery : An ALE meta-analysis. *Neuroscience &*
638 *Biobehavioral Reviews*. 2013;37(5), 930-949.<https://doi.org/10.1016/j.neubiorev.2013.03.017>

639

640 51. Humphrey N, Mullins, Patricia M. Self-Concept and Self-Esteem in Developmental
641 Dyslexia: Implications for Theory and Practice. Journal of Research in Special Educational
642 Needs. 2002;v2(n2):p1-13.
643

644 52. Hyde C, Wilson P. Online motor control in children with developmental coordination
645 disorder: chronometric analysis of double-step reaching performance: Online motor control in
646 children with developmental coordination disorder. Child: Care, Health and Development.
647 Janu 2011;37(1):111-22.
648

649 53. Hyde CE, Wilson PH. Impaired Online Control in Children With Developmental
650 Coordination Disorder Reflects Developmental Immaturity. Developmental
651 Neuropsychology. Febr 2013;38(2):81-97.
652

653 54. Hyde C, Fuelscher I, Buckthought K, Enticott PG, Gitay MA, Williams J. Motor imagery
654 is less efficient in adults with probable developmental coordination disorder: Evidence from
655 the hand rotation task. Research in Developmental Disabilities. Nov 2014;35(11):3062-70.
656

657 55. Hyde, C., Fuelscher, I., Williams, J., Lum, J. A. G., He, J., Barhoun, P., & Enticott, P. G.
658 Corticospinal excitability during motor imagery is reduced in young adults with
659 developmental coordination disorder. Research in Developmental Disabilities. 2018 ; 72,
660 214-224. <https://doi.org/10.1016/j.ridd.2017.11.009>
661

662 56. Ionta S, Fourkas AD, Fiorio M, Aglioti SM. The influence of hands posture on mental
663 rotation of hands and feet. Exp Brain Res. 19 sept 2007;183(1):1-7.
664

665 57. Iosa, M., Zoccolillo, L., Montesi, M., Morelli, D., Paolucci, S., & Fusco, A. The brain's
666 sense of walking : A study on the intertwine between locomotor imagery and internal
667 locomotor models in healthy adults, typically developing children and children with cerebral
668 palsy. *Frontiers in Human Neuroscience*. 2014 ; 8, 859.
669 <https://doi.org/10.3389/fnhum.2014.00859>
670
671 58. Jeannerod M. Mental imagery in the motor context. *Neuropsychologia*. Nov
672 1995;33(11):1419-32.
673
674 59. Jonas N. Pour les générations les plus récentes, les difficultés des adultes diminuent à
675 l'écrit, mais augmentent en calcul. 2012;4.
676
677 60. Kagerer FA, Bo J, Contreras-Vidal JL, Clark JE. Visuomotor Adaptation in Children with
678 Developmental Coordination Disorder. *Motor Control*. Oct 2004;8(4):450-60.
679
680 61. Kalicinski, M., Kempe, M., & Bock, O. Motor Imagery : Effects of Age, Task
681 Complexity, and Task Setting. *Experimental Aging Research*. 2015; 41(1), 25-38.
682 <https://doi.org/10.1080/0361073X.2015.978202>
683
684 62. Kaltner S, Jansen P. Mental rotation and motor performance in children with
685 developmental dyslexia. *Research in Developmental Disabilities*. March 2014;35(3):741-54.
686
687 63. Kreutzer JS, DeLuca J, Caplan B, éditeurs. *Encyclopedia of Clinical Neuropsychology*.
688 Cham: Springer International Publishing; 2018.
689

690 64. Lefavrais, P. Alouette-R. Les éditions du centre de psychologie appliquée. 2005;
691

692 65. Lejeune C, Wansard M, Geurten M, Meulemans T. Procedural learning, consolidation,
693 and transfer of a new skill in Developmental Coordination Disorder. *Child Neuropsychology*.
694 17 febr 2016;22(2):143-54.
695

696 66. Licari MK, Reynolds JE. Understanding Performance Variability in Developmental
697 Coordination Disorder: What Does It All Mean? *Curr Dev Disord Rep*. June 2017;4(2):53-9.
698

699 67. Lorås H, Sigmundsson H. Interrelations between Three Fine Motor Skills in Young
700 Adults. *Percept Mot Skills*. Aug 2012;115(1):171-8.
701

702 68. Lum JAG, Ullman MT, Conti-Ramsden G. Procedural learning is impaired in dyslexia:
703 Evidence from a meta-analysis of serial reaction time studies. *Research in Developmental*
704 *Disabilities*. Oct 2013;34(10):3460-76.
705

706 69. Macdonald SJ, Deacon L. Twice upon a time: Examining the effect socio-economic status
707 has on the experience of dyslexia in the United Kingdom. *Dyslexia*. Feb 2019;25(1):3-19.
708

709 70. Malouin, F., Belleville, S., Richards, C. L., Desrosiers, J., & Doyon, J. Working memory
710 and mental practice outcomes after stroke. *Archives of Physical Medicine and Rehabilitation*.
711 2004; 85(2), 177-183. [https://doi.org/10.1016/S0003-9993\(03\)00771-8](https://doi.org/10.1016/S0003-9993(03)00771-8)
712

- 713 71. Marquet-Doléac, J. S R, Albaret, J. M. MABC-2 Batterie d'évaluation du mouvement
714 chez l'enfant -2e édition- adaptation française. Edition du centre de psychologie appliquée.
715 2016;
716
- 717 72. Martel M, Cardinali L, Roy AC, Farnè A. Tool-use: An open window into body
718 representation and its plasticity. *Cognitive Neuropsychology*. 17 féb 2016;33(1-2):82-101.
719
- 720 73. Miall, R. C., Wolpert, D. M. Forward models for physiological motor control. *Neural*
721 *Networks*. 1996;
722
- 723 74. Moe-Nilssen R, Helbostad JL. Interstride trunk acceleration variability but not step width
724 variability can differentiate between fit and frail older adults. *Gait & Posture*. Feb
725 2005;21(2):164-70.
726
- 727 75. Naito E, Kochiyama T, Kitada R, Nakamura S, Matsumura M, Yonekura Y, et al.
728 Internally Simulated Movement Sensations during Motor Imagery Activate Cortical Motor
729 Areas and the Cerebellum. *J Neurosci*. 1 may 2002;22(9):3683-91.
730
- 731 76. Nalavany BA, Logan JM, Carawan LW. The relationship between emotional experience
732 with dyslexia and work self-efficacy among adults with dyslexia. *Dyslexia*. Febr
733 2017;24(1):17-32.
734
- 735 77. Nergård-Nilssen T, Hulme C. Developmental Dyslexia in Adults: Behavioural
736 Manifestations and Cognitive Correlates: Developmental Dyslexia in Adults. *Dyslexia*. Aug
737 2014;20(3):191-207.

738

739 78. Nicolson RI, Fawcett AJ. Developmental dyslexia: The role of the cerebellum. 1999;23.

740

741 79. Papaxanthis C, Schieppati M, Gentili R, Pozzo T. Imagined and actual arm movements

742 hAve similar durations when performed under different conditions of direction and mass. Exp

743 Brain Res. Apr 2002;143(4):447-52.

744

745 81. Pennington B. From single to multiple deficit models of developmental disorders.

746 Cognition. Sept 2006;101(2):385-413.

747

748 82. Personnier, P., Kubicki, A., Laroche, D., & Papaxanthis, C. Temporal features of

749 imagined locomotion in normal aging. Neuroscience Letters. 2010;476(3), 146-149.

750 <https://doi.org/10.1016/j.neulet.2010.04.017>

751

752 83. Pulvermüller F. Brain mechanisms linking language and action. Nat Rev Neurosci. July

753 2005;6(7):576-82.

754

755 84. Ramus F. Theories of developmental dyslexia: insights from a multiple case study of

756 dyslexic adults. Brain. 1 apr 2003;126(4):841-65.

757

758 85. Ramus F, Pidgeon E, Frith U. The relationship between motor control and phonology in

759 dyslexic children. J Child Psychol Psychiatry. July 2003;44(5):712-22.

760

761 86. Ramus F, Szenkovits G. What Phonological Deficit? Quarterly Journal of Experimental

762 Psychology. Janu 2008;61(1):129-41.

763

764 87. Raven, J. C., Court, J. H., Raven, J. Raven's progressive matrices and vocabulary scales.
765 Oxford Psychologists Press. 1995;

766

767 88. Rizzolatti G, Fogassi L, Gallese V. Neurophysiological mechanisms underlying the
768 understanding and imitation of action. *Nat Rev Neurosci*. Sept 2001;2(9):661-70.

769

770 89. Rizzolatti G, Fogassi L, Gallese V. Motor and cognitive functions of the ventral premotor
771 cortex. *Current Opinion in Neurobiology*. Apr 2002;12(2):149-54.

772

773 90. Scerrati E, Baroni G, Borghi AM, Galatolo R, Lugli L, Nicoletti R. The modality-switch
774 effect: visually and aurally presented prime sentences activate our senses. *Front Psychol*. 30
775 oct 2015;6.

776

777 91. Schmitz C, Assaiante C. Developmental sequence in the acquisition of anticipation during
778 a new co-ordination in a bimanual load-lifting task in children. *Neuroscience Letters*. Sept
779 2002;330(3):215-8.

780

781 92. Schmitz C, Martin N, Assaiante C. Development of anticipatory postural adjustments in a
782 bimanual load-lifting task in children. *Experimental Brain Research*. 4 may
783 1999;126(2):200-4.

784

785 93. Schwartz J-L, Basirat A, Ménard L, Sato M. The Perception-for-Action-Control Theory
786 (PACT): A perceptuo-motor theory of speech perception. *Journal of Neurolinguistics*. Sept
787 2012;25(5):336-54.

788

789 94. Shaywitz SE, Shaywitz BA. Dyslexia (Specific Reading Disability). *Biological*
790 *Psychiatry*. June 2005;57(11):1301-9.

791

792 95. Sinani C, Sugden DA, Hill EL. Gesture production in school vs. clinical samples of
793 children with Developmental Coordination Disorder (DCD) and typically developing
794 children. *Research in Developmental Disabilities*. July 2011;32(4):1270-82.

795

796 96. Sirigu A, Duhamel JR. Motor and Visual Imagery as Two Complementary but Neurally
797 Dissociable Mental Processes. *Journal of Cognitive Neuroscience*. 1 oct 2001;13(7):910-9.

798

799 97. Sirigu, A., Cohen, L., Duhamel, J. R., Pillon, B., Dubois, B., Agid, Y., et al. Congruent
800 unilateral impairments for real and imagined hand movements. *Cognitive Neuroscience and*
801 *Neuropsychology*. 1995;

802

803 98. Skoura X, Vinter A, Papaxanthis C. Mentally Simulated Motor Actions in Children.
804 *Developmental Neuropsychology*. 11 may 2009;34(3):356-67.

805

806 99. Smits-Engelsman, B. C. M., Blank, R., Van der Kaay, A. C., MOsterd Van der Meijs, R.,
807 Vlugt Van den Brand, E., Polatjko, H. J., et al. Efficacy of interventions to improve motor
808 performance in children with developmental coordination disorder: a combined systematic
809 review and meta-analysis. *Developmental medicine&child neurology*. 2012;

810 Smits-Engelsman, B., Blank, R., Kaay, A.-C., Meijs, R., Brand, E., Polatajko, H., & Wilson, P.

811 (2012). Efficacy of interventions to improve motor performance in children with

812 developmental coordination disorder : A combined systematic review and meta-analysis.
813 *Developmental medicine and child neurology*, 55. <https://doi.org/10.1111/dmcn.12008>
814
815 Cignetti F, Fontan A, Menant J, Nazarian B, Anton JL, Vaugoyeau M, Assaiante C.
816 Protracted Development of the Proprioceptive Brain Network During and Beyond
817 Adolescence. *Cereb Cortex*. 2017 Feb 1;27(2):1285-1296. doi: 10.1093/cercor/bhv323.
818 PMID: 26733535.
819 100. Snowling, M.J. *Dyslexia*. (2nd Ed.) Oxford: Blackwell. 2000;
820
821 101. Stoodley CJ. The Role of the Cerebellum in Developmental Dyslexia. In: *The Linguistic*
822 *Cerebellum*. Elsevier; 2016. p. 199-221.
823
824 102. Stoodley CJ, Stein JF. Cerebellar Function in Developmental Dyslexia. *Cerebellum*. Apr
825 2013;12(2):267-76.
826
827 103. Swanson HL, Hsieh C-J. Reading Disabilities in Adults: A Selective Meta-Analysis of
828 the Literature. *Review of Educational Research*. Déc 2009;79(4):1362-90.
829
830 104. van Bergen E, van der Leij A, de Jong PF. The intergenerational multiple deficit model
831 and the case of dyslexia. *Frontiers in Human Neuroscience*. 2 June 2014;8.
832
833 105. van de Walle de Ghelcke A, Skoura X, Edwards MG, Quercia P, Papaxanthis C. Action
834 representation deficits in adolescents with developmental dyslexia. *J Neuropsychol*. 20 Aug
835 2020;jnp.12220.
836

837 106. Vargas CD. The Influence of Hand Posture on Corticospinal Excitability during Motor
838 Imagery: A Transcranial Magnetic Stimulation Study. *Cerebral Cortex*. 13 May
839 2004;14(11):1200-6.
840

841 107. Vellutino FR, Fletcher JM, Snowling MJ, Scanlon DM. Specific reading disability
842 (dyslexia): what have we learned in the past four decades? *J Child Psychol & Psychiat*. Janu
843 2004;45(1):2-40.
844

845 108. Warlop, G., Vansteenkiste, P., Lenoir, M., Van Causenbroeck, J., & Deconinck, F. J. A.
846 Gaze behaviour during walking in young adults with developmental coordination disorder.
847 *Human Movement Science*. 2020 ; 71, 102616. <https://doi.org/10.1016/j.humov.2020.102616>
848

849 109. Watkins KE, Strafella AP, Paus T. Seeing and hearing speech excites the motor system
850 involved in speech production. *Neuropsychologia*. Janu 2003;41(8):989-94.
851

852 110. Wilmut K. Performance Under Varying Constraints in Developmental Coordination
853 Disorder (DCD): Difficulties and Compensations. *Curr Dev Disord Rep*. June
854 2017;4(2):46-52.
855

856 111. Wilson M, Knoblich G. The Case for Motor Involvement in Perceiving Conspecifics.
857 *Psychological Bulletin*. 2005;131(3):460-73.
858

859 112. Wilson PH, Maruff P, Butson M, Williams J, Lum J, Thomas PR. Internal representation
860 of movement in children with developmental coordination disorder: a mental rotation task.
861 *Developmental Medicine & Child Neurology*. 2004;46(11):754-9.

862

863 113. Wilson PH, Ruddock S, Smits-Engelsman B, Polatajko H, Blank R. Understanding
864 performance deficits in developmental coordination disorder: a meta-analysis of recent
865 research: Review. *Dev Med Child Neurol*. Marc 2013;55(3):217-28.

866

867 114. Wilson PH, Smits-Engelsman B, Caeyenberghs K, Steenbergen B, Sugden D, Clark J, et
868 al. Cognitive and neuroimaging findings in developmental coordination disorder: new insights
869 from a systematic review of recent research. *Dev Med Child Neurol*. Nov
870 2017;59(11):1117-29.

871

872 115. Wolpert DM, Flanagan JR. Motor prediction. *Current Biology*. Sept
873 2001;11(18):R729-32.

874

875 116. Wolpert DM, Miall RC, Kawato M. Internal models in the cerebellum. *Trends in*
876 *Cognitive Sciences*. Sept 1998;2(9):338-47.

877

878 117. Zoia S, Barnett A, Wilson P, Hill E. Developmental Coordination Disorder: current
879 issues. *Child Care Health Dev*. nov 2006;32(6):613-8.

880

881 118. Zwicker JG, Missiuna C, Harris SR, Boyd LA. Brain activation associated with motor
882 skill practice in children with developmental coordination disorder: an fMRI study. *Int j dev*
883 *neurosci*. avr 2011;29(2):145-52.

884

885

886