Motor deficits in reading disability and language impairment: same or different?

Several studies have found evidence of motor deficits in poor readers. There is no obvious reason for motor and literacy skills to go together, and it has been suggested that both deficits could be indicative of an underlying problem with cerebellar function and/or procedural learning. However, the picture is complicated by the fact that reading problems often co-occur with oral language impairments, which have also been linked with motor deficits. This raises the question of whether motor deficits characterise poor readers when language impairment has been accounted for – and vice versa. We considered these questions by assessing motor deficits associated with RD and LI. A large community sample provided a subset of 9- to 10-year-olds, selected to oversample children with reading and/or language difficulties, to give 48 children with comorbid LI+RD, 70 children with RD only, 34 children with LI only, and 170 typically-developing (TD) children with neither type of difficulty. These children were given four motor tasks that taxed speed, sequence, and imitation abilities to differing extents. A double dissociation emerged, such that RD was associated with poor performance on a fingertip sequencing task, whereas LI was not. In contrast, LI but not RD was associated with problems in imitating hand positions. Poor performance on a speeded peg-moving task that required a precision grip was found in both LI and RD, with the poorest performance on those with comorbid LI+RD. This study confirms that RD is associated with poor motor skills, even when LI has been accounted for, but the deficits are specific to particular tasks that involve a combination of speed and precision. The associations were reliable, but the effect sizes were relatively small, consistent with the idea that there may be overlapping risk factors for motor deficits and poor reading.

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1   **Introduction**

2   It has been noted for many years that children who are poor readers may also show

3   signs of clumsiness and poor fine motor control. In an early epidemiological study, Rutter and

4   Yule (1970) found an excess of motor impairments in children who were poor readers relative

5   to their IQ ('specific reading retardation'), regardless of whether this was assessed by parental

6   report, clinical observation or direct assessment. This kind of observation has been used as

7   evidence that reading disability is not just the result of poor teaching, but has a neurological

8   basis (Ramus, 2004). However, the link between motor impairment and literacy problems

9   remains poorly understood.

10   One complication is that it remains unclear whether motor impairments are a genuine

11   correlate of reading disability, or whether they are linked more closely to other problems that

12   co-occur with poor reading. Many children diagnosed with reading disability (or

13   'developmental dyslexia') also have oral language problems, but these may be overlooked if

14   language is not formally assessed (Bishop & Snowling, 2004). Studies of children with

15   language impairments provide ample evidence that motor deficits are common in this

16   population. These observations raise two related questions. Will we find evidence of motor

17   impairment if we focus only on poor readers who do not have oral language problems? And if

18   motor deficits are seen in children with combined reading and language impairments, are they

19   the same as those in children who read well despite oral language problems?

20   Another issue concerns the variation in how motor skills are measured. Previous

21   studies have included both fine and gross motor skills, tasks that stress speed vs. those

22   stressing precision, and tasks that involve learning vs. those that do not. We need to clarify

23   whether reading disability and language impairment are associated with distinct types of

24   motor difficulty. The answer to this question has implications for our understanding of

25   possible neurological underpinnings of children's language and literacy problems.

26   In the current study we used the term "reading disability" (RD) rather than

27   developmental dyslexia, defining RD in terms of low scores on a quantitative measure of

28   reading accuracy in the context of normal range nonverbal IQ. A group defined this way

29   overlaps substantially with those typically studied as cases of developmental dyslexia, but the

30   nomenclature emphasises that this is not a clear-cut syndrome with sharp diagnostic

31   boundaries. Furthermore, in line with most current practice, we do not distinguish between

32   children with a substantial discrepancy between nonverbal IQ and reading or language and

33   those with more even cognitive profiles (Stanovich, 1991). Our approach to language

34   impairment (LI) is similar. Here too, several lines of research indicate that the nature and

35   causes of language impairment are similar, regardless of whether there is a large discrepancy

36   with nonverbal IQ, provided IQ is broadly within normal limits (Bishop, 1994). We focus on

37   children scoring at the low end of reading and language ability, because these are children

38   who attract professional concern, but this does not mean that we regard RD and LI as

39   disorders that are distinct from normal variation.

40   Our first question is whether motor deficits are associated with both RD and LI.

41   Because many children have both reading and language difficulties, the existing literatures on

42   dyslexia and LI cannot answer this question: we need a study of children who have been

43   explicitly assessed for both oral and written language abilities. Second, we can ask what kinds

44   of motor impairment are most closely linked with reading and/or language problems. Various

45   possible explanations need to be considered. It could be that the motor deficit co-occurs with

46   other disorders because the causal factors that lead to RD and/or LI are correlated with causal

47   factors that lead to motor problems. For instance, genetic variants that affect the risk for RD

48   may affect development of motor systems as well. Or the link may go beyond common causes

49   to involve shared underlying cognitive processes – for instance, difficulties in speed of

50   processing or sequencing. In terms of this second type of explanation, different theoretical

51   accounts of developmental disorders predict specific problems with different aspects of

52   movement, such as speed, sequencing or motor imitation. Thus, by pinpointing the nature of

53   motor deficits that co-occur with reading or language difficulties, we may cast light on

54   cognitive underpinnings of these disorders, clarifying whether they have similar origins.

55   We will first review what is known about different motor abilities in relation to

56   reading and language impairments and then present new data on a large sample of children

57   assessed for both language and literacy skills.

58   *Speed*

59   Slow motor movements have been reported in individuals with reading difficulties, on

60   tasks such as peg-moving and bead-threading (Fawcett & Nicolson, 1995; Stoodley & Stein,

61   2006), and foot-tapping (Fawcett & Nicolson, 1999). Fawcett & Nicolson (1999) saw these

62   findings as consistent with their theory of cerebellar impairment in dyslexia, as cerebellar

63   patients show similar deficits in these tasks. Morris et al. (1998) reported deficits in

64   finger-tapping and finger dexterity in children with reading disability, especially in children

65   who were poor at a task of rapid serial naming. However, Gaysina, Maughan and Richards

66   (2010) found no association between speed on a simple finger-tapping task and poor reading

67   in a population cohort of 15-year-olds.

68   In a review of motor skills in SLI, Hill (2001) noted that deficits were usually found

69   on speeded motor tasks. An early demonstration of this was by Bishop and Edmundson

70   (1987), who suggested that motor speed might be a marker of neurodevelopmental maturity.

71   They found that on a peg-moving task many 4-year-olds with language impairments improved

72   from the impaired to the normal range over an 18-month follow-up period, with a close

73   parallel between improvement in language skills and motor speed. They suggested a possible

74   maturational lag in language impaired children, where the duration of the lag is related to the

75   severity of language impairment. Bishop (2002) replicated the finding of slower peg-moving

76   in an older group of language-impaired children, and also demonstrated deficits on a simple

77   task that involved tapping a tally counter with the thumb as quickly as possible. Hill (2001)

78   suggested that slow motor performance might be part of a more general slowing of cognitive

79   processing, which has been proposed to affect SLI across several modalities (Kail, 1994).

80   *Sequencing*

81   Advocates of the cerebellar theory of dyslexia have noted impairments of sequencing

82   in individuals with dyslexia (Nicolson & Fawcett, 2007). Consistent with this, Stoodley,

83   Harrison and Stein (2006) found that implicit motor learning was poor in adults with dyslexia:

84   on a serial reaction time task, their speed did not improve when the sequence of stimuli was

85   repeated, whereas controls showed implicit learning. In a similar vein, an underlying deficit

86   in the learning of serial-order information has been described in developmental dyslexia, on

87   the basis of impaired Hebbian learning (Szmalec et al., 2011). The Hebb tasks involved

88   implicit learning of the sequence of perceived stimuli, rather than motor sequencing.

89   However, if this kind of learning was impaired in SLI or dyslexia, it could lead to problems in

90   automatizing the sequence of movements involved in motor tasks.

91   The ability to perform a sequence of actions has also been studied in children with

92   language impairments. Bishop and Edmundson (1987) noted that children with SLI made

93   more sequence errors in peg-moving than controls; picking up pegs in the wrong order, or

94   placing them in the wrong hole. Hill, Bishop, and Nimmo-Smith (1998) interpreted the

95   greater errors in representational gesture production as an inability to implement the precise

96   sequence of movements in children with SLI. More recently, several studies have

97   demonstrated impairments of implicit motor learning on the serial reaction time task in

98   children with SLI (Tomblin, Mainela-Arnold, & Zhang, 2007; Lum et al., 2010, 2012;

99   Mayor-Dubois et al., 2012; Gabriel et al., 2013; H J Hsu & D V M Bishop, unpublished data).

100   These studies were prompted by the procedural deficit hypothesis of Ullman and Pierpont

101   (2005) who suggested that children with SLI have abnormalities in the procedural memory

102   system, affecting the ability to learn both linguistic and non-linguistic sequences. Nicolson

103   and Fawcett (2007) took this idea further, suggesting that dyslexia and SLI might be caused

104   by impairments in different parts of the procedural learning system, with the

105   cortico-cerebellar system implicated in dyslexia, and the cortico-striatal system in SLI.

106   However, no studies have directly compared children with these two disorders on the same

107   task.

108   *Imitation*

109   Problems with motor imitation are usually thought of as characterising autistic

110   disorder, where they are seen as part of a more general problem in social cognition (Williams,

111   Whiten, Suddendorf, & Perrett, 2001). However, given that imitation is a key ingredient in

112   language learning, it is worth considering whether children with SLI might also have

113   problems with imitating, even in nonverbal contexts. A study by Vukovic, Vukovic, and

114   Stojanovik (2010) suggested this may be the case. They asked children to imitate simple and

115   complex movements, with fingers, hands, and arms. Children with SLI were able to imitate

116   significantly fewer movements than typically developing children, showing a marked

117   impairment even for simple movements, whereas control children performed at ceiling levels.

118 Consistent with this was a study by Dohmen, Chiat and Roy (in press), who found deficits in

119 imitation of non-instrumental movements by much younger language-delayed children aged

120 from 2 to 3 years.

121 These findings of deficits in imitation contrast with earlier findings by Hill (1998),

122 who compared various tasks of motor praxis in children with SLI and those with

123 Developmental Co-ordination Disorder (DCD). She found that when asked to copy

124 meaningless hand postures and sequences, children with DCD or SLI performed as well as

125 peers, though interpretation of this result was complicated by ceiling effects. Other results

126 from Hill (1998), however, seem to contradict the idea of an imitation deficit in SLI. When

127 producing representational gestures of familiar motor acts, children with SLI and children

128 with DCD made more errors than age-matched children, and performed at a similar level to

129 typically-developing children who were 4 years younger; importantly, this was found

130 regardless of whether the child had to imitate the gesture, or generate it from verbal

131 command. Hill concluded that when performing familiar actions, kinaesthetic information

132 may be especially important, and she suggested that the praxic difficulties of children with

133 SLI and those with DCD may have kinaesthetic origins.

134 *Current Study*

135 The current study compared children with RD and those with LI to

136 typically-developing (TD) children on motor tests that varied in the demands they placed on

137 speed, imitation and sequential order. No other study has looked closely at the motor abilities

138 of these two groups on the same tasks. As well as considering differences between children

139 scoring in the impaired range on reading and oral language measures, we examined

140 correlations between quantitative measures of speech, language and reading skills.

141 **Method**

142 *Participants*

143   The initial sample included 388 same-sex twins recruited through the Twins Early

144 Development Study (TEDS), a community sample of twins born in England and Wales

145 (Trouton, Spinath, & Plomin, 1994). The selection and categorisation of this particular

146 subsample has been described in detail by Bishop, McDonald, Bird, and Hayiou-Thomas

147 (2009). As previously described, this sample was enriched with cases of language and literacy

148 problems by oversampling children who had been identified as having difficulties in these

149 areas on previous waves of testing. Children with nonverbal IQs less than 80 or greater than

150 120 were excluded. In addition, potential participants were excluded if they had evidence of

151 hearing loss, autism, physical handicap, or a language spoken at home other than English. A

152 further 16 were excluded from the current study due to incomplete data on motor measures.

153 This left 322 participants who were aged 9 or 10 years at the time of testing ($M = 9.54$, $SD = .$

154 37).

155   Children were first grouped according to reading ability. Children were classified as

156 having reading disability (RD) if their average score on two Test of Word Reading Efficiency

157 (TOWRE; Torgesen, Wagner, & Rashotte, 1999) subtests was below the 13th percentile.

158 Children were also categorised according to language ability, either as language typical or

159 language impaired (LI). Where a child had at least two scores more than 1.33 *SD* below the

160 normative mean on five core language measures (see below for details), they were categorised

161 as LI.

162   The final sample consisted of 48 children (18 girls and 30 boys) with comorbid

163 LI+RD, 34 children (16 girls and 18 boys) with LI only, 70 children (34 girls and 36 boys)

164 with RD only, and 170 children (99 girls and 71 boys) who met criteria for neither disorder

165 (typically developing, TD).

166   Data collection conformed to the Declaration of Helsinki, and ethics approval was

167 obtained from Oxford University's Experimental Psychology Research Ethics Committee.

168 Parents of participating children gave informed consent, and children gave verbal assent, as

169 agreed by the Ethics Committee.

170 *Language and reading tasks*

171 Core diagnostic tests. The battery of five core language tests, used to define LI, included

172 expressive and receptive tests of vocabulary and sentence processing: (1) Vocabulary subtest

173 from the Wechsler Abbreviated Scale of Intelligence (WASI: Wechsler, 1999); (2)

174 Understanding Directions subtest from the Woodcock-Johnson III (Woodcock, McGrew, &

175 Mather, 2001); (3) Comprehension subtest from Expressive, Receptive and Recall of

176 Narrative Instrument (ERRNI; Bishop, 2004); (4) Mean Length of Utterance from the

177 ERRNI; (5) NEPSY Sentence repetition (Korkman, Kirk, & Kemp, 1998). Reading was

178 assessed using the TOWRE Phonological decoding efficiency and Word reading efficiency

179 subtests (Torgesen et al., 1999). These assess speeded reading of real words and nonwords.

180 Scores on the two reading subtests are highly correlated, and were averaged.

181 Supplementary language and literacy tests. Two additional subtests from the NEPSY,

182 oromotor skills and nonword repetition were used to assess speech production and

183 phonological memory respectively (Korkman et al., 1998). An average score was obtained

184 from the Pictures and Digits Rapid Serial Naming subtests of the Phonological Assessment

185 Battery (Frederickson, Frith, & Reason, 1997). Scores for reading accuracy, comprehension

186 and rate were obtained from a shortened version of the Neale Analysis of Reading Ability

187 (Neale, 1997), which assesses reading of meaningful texts.

188 Nonverbal ability. The Block Design subtest from the WASI was administered as a measure

189 of nonverbal ability (Wechsler, 1999).

190 All tests are standardized, but scores were restandardized relative to a normative set of twins

191 who were representative of the whole population, to ensure comparability of norms across

192 tests (see Bishop et al., 2009 for further details and for information on reliability of measures).

193 *Motor tasks*

194 Motor tasks were interleaved within the battery of language and reading ability tests,

195 in a session lasting no longer than 2 hours.

196 NEPSY Repetitive Fingertip Tapping (Korkman et al., 1998) is a task designed to

197 assess finger dexterity and motor speed. Children were required to tap their index finger to

198 their thumb on the same hand, making a circular shape. The experimenter demonstrated, and

199 children were instructed to repeat this action as fast as possible. The time was noted for 32

200 correct taps. This procedure was administered using the child's preferred hand, and then

201 repeated with the non-preferred hand. The mean time for 32 taps was inverted to give taps per

202 second, so that proficient performance corresponded to a high score.

203 NEPSY Sequential Fingertip Tapping (Korkman et al., 1998) is aimed at assessing

204 finger dexterity and motor speed, and includes sequential movement. Children sequentially

205 tapped their thumb to each finger of the same hand, from index to little finger. Participants

206 were asked to repeat this sequence as fast as possible, and timed for 8 correct sequences. They

207 first completed the sequences with their preferred hand, and then their non-preferred hand.

208 The mean time for eight sequences was inverted to give sequences per second, so that

209 proficient performance corresponded to a high score.

210   The Purdue Pegboard tests manipulative dexterity, and was administered according to

211 the procedure described by Tiffin (1968). This task was selected to assess precision grip,

212 which is known to depend on cerebellar activity (Monzée, Drew, & Smith, 2004). The task

213 also includes a speed element, as children were given 30 seconds to move as many small pegs

214 into individual peg holes (in a top-to-bottom line) as possible. Participants completed the task

215 twice with their preferred hand, then their non-preferred hand, giving a total of 4 trials.

216   NEPSY Imitating Hand Positions (Korkman et al., 1998) assesses the ability to imitate

217 hand and finger positions. Children were instructed to copy hand positions administered by

218 the experimenter. A maximum of 20 seconds was allowed for each of the 12 hand positions.

219 One point was awarded for each correct hand position within the time limit. Again children

220 first completed the task with their preferred hand, and then with their non-preferred hand.

221 *Analytic approach*

222   Previous research has not found reliable effects of language or literacy on relative

223 hand skill (Bishop, 1990, 2001), and so scores for preferred and non-preferred hands were

224 combined to form a composite score for each motor task. Scores were inspected and

225 transformations applied if necessary to correct for non-normality. A natural log transform was

226 used for the two NEPSY Fingertip Tapping tasks, and a rank transform for NEPSY Imitating

227 Hand Positions.

228   Our primary goal was to consider how language and reading status affected motor

229 performance on the different tasks, and so we included the binary categories of RD and LI as

230 factors in SPSS multilevel linear models for each motor task. The interaction between LI and

231   RD was also tested to see whether the combination of both conditions had a greater impact

232   than would be predicted from their separate effects. Sex was included as a covariate in the

233   model. Because our participants were twins, the individual observations were not

234   independent. This was taken into account by including family membership as a random effect

235   in the multilevel models. Effect sizes for significant main effects are reported as Cohen's d,

236   based on difference in estimated marginal means divided by the pooled standard deviation.

237   Analysis of RD and LI effects allows us to relate results to the prior literature on

238   dyslexia and SLI, but these categories involve arbitrary subdivisions of continuous scales of

239   language and reading ability. To explore the data in a more quantitative fashion, two-tailed

240   Pearson correlations were computed for language and reading task standard scores with

241   transformed motor scores, for supplementary as well as core diagnostic tests. Because of the

242   large number of correlations computed, there is a risk of finding spurious associations, but the

243   twin design of our study allowed for a natural replication study. Twins from each family were

244   assigned randomly into twin group 1 or twin group 2 and correlations were run separately for

245   each twin group, so we could establish how replicable significant correlations were.

246   **Results**

247   *Multilevel modelling*

248   Figure 1 shows mean raw scores on the four motor tests in relation to language and

249   reading impairment. Log- or rank-transformed scores, as described above, were used in the

250   analysis where appropriate to improve normality. F-ratios for the multilevel linear models are

251   shown in Table 1.

252   Different patterns of results were found for the four motor tasks. On the NEPSY

253 Repetitive Fingertip Tapping task, there was no significant effect of language impairment or

254 reading disability, and no interaction between these factors. For NEPSY Sequential Fingertip

255 Tapping, there was a significant effect of reading disability, but no effect of language

256 impairment, and no interaction between these factors. In contrast, on the Purdue Pegboard,

257 there was a substantial effect of language impairment, and a smaller but significant effect of

258 reading disability. As can be seen in Figure 1, the lowest scores were obtained by those with a

259 dual deficit of LI with RD, but this could be explained as an additive influence of the two

260 conditions, as the interaction between them was not significant. This pattern of results was

261 maintained when sex-corrected scores were used in the analysis. On the NEPSY Imitation of

262 Hand Positions test, there was a significant effect of language impairment. The effect of

263 reading disability was not significant and there was no interaction between the two conditions.

264 *Correlations*

265   Figure 2 shows the correlations between cognitive tests and motor tests in the two

266 subsamples of twins (each containing one member of a twin pair, selected at random). For a

267 sample of this size, a correlation of .16 is significant at .05 level, a correlation of .20 is

268 significant at .01 level, and a correlation of .26 is significant at .001 level. None of the

269 correlations with finger-tapping were consistently found in both samples at the .05 level.

270   The NEPSY Sequential Fingertip Tapping task had consistent, though modest,

271 correlations with many of the literacy tasks, but was not reliably correlated with three of the

272 core language measures: MLU, story comprehension or vocabulary. For this task, the highest

273 correlation in both subsamples was with NEPSY Oromotor Sequences, suggesting that there

274 may be a common core involvement of motor systems in sequencing speech and finger

275   movements. On the other hand, it is also noteworthy that all three of the indices from the

276   Neale Analysis of Reading Ability were significantly correlated with finger sequencing, even

277   though this task is not speeded and has limited motor demands.

278   The Purdue Pegboard task was reliably correlated with most of the tasks in the test

279   battery, whereas NEPSY Imitation of Hand Positions showed an inconsistent pattern of

280   correlations in the two subsamples of twins. Only nonverbal ability and WASI Vocabulary

281   were consistently significantly correlated with this test in both subsamples. The correlational

282   analysis casts some doubt on the reliability of the association of this subtest with language

283   impairment, because associations with Woodcock-Johnson Comprehension, NEPSY Sentence

284   Repetition and ERRNI MLU were seen in only one of the two subgroups of twins.

285   **Discussion**

286   This study confirmed that motor impairments are associated with RD, even when it

287   occurs without LI; however, there were different patterns of association for the two disorders

288   suggesting that the underlying reasons for motor deficits are not the same.

289   *Speed*

290   Three of the motor tasks stressed speed: NEPSY Repetitive Fingertip Tapping,

291   NEPSY Sequential Fingertip Tapping and the Purdue Pegboard. The simplest of these tasks,

292   Repetitive Fingertip Tapping, did not discriminate groups: children with reading disability or

293   language impairment were as fast as typically-developing children on this measure. This

294   contrasts with a previous study by Bishop (2002), who found reduced speed on a

295   thumb-tapping task in language-impaired children. However, that task involved repeatedly

296   depressing the switch on a tally counter, a novel movement which some children found

28

297 difficult to do with one hand. Our current data show that if the task demands are reduced to

298 the bare minimum, children with developmental disorders of language and reading can

299 perform as fast as other children.

300   When the child had to sustain a repetitive sequence of finger movements, however, a

301 small deficit was seen in children with RD, and when the task was to quickly pick up and

302 place small metal components with a precision grip, there were significant deficits associated

303 with both LI and RD, with particularly poor performance by children who had comorbid

304 LI+RD. These findings are compatible with previous research that has found that peg-moving

305 tasks are sensitive indicators of motor deficits in both SLI (Bishop & Edmundson, 1987) and

306 dyslexia (Fawcett & Nicolson, 1995).

307 *Sequencing*

308   Problems in sequencing motor movements have been observed in children with SLI

309 doing peg-moving (Bishop & Edmundson, 1987) and gesture production (Hill et al., 1998),

310 and impaired sequence learning has been observed in serial reaction time tasks in both

311 dyslexia (Stoodley et al., 2006) and SLI (e.g. Tomblin et al., 2007). In the current study, the

312 one task that involved explicitly producing a sequence of motor movements, NEPSY

313 Sequential Fingertip Tapping, showed a deficit for RD but not for LI. Note, however, that the

314 NEPSY Sequential Fingertip Tapping task is very simple, and the sequence of movements is

315 predictable. Furthermore, the correlational analysis revealed that this motor task was

316 associated with a measure of oromotor skills (repeating tongue-twisters). This task had not

317 been included in the diagnostic battery for LI, because it stresses articulation rather than

318 language ability.

319 *Imitation*

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320   Imitation tasks have shown that language impaired children successfully imitate fewer

321   movements than peers (Vukovic et al., 2010), though for one study this was only true for

322   familiar gestures (Hill, 1998). The current study confirmed that language impaired children

323   correctly imitated fewer hand positions, despite the fact that most of these were novel

324   gestures. The correlational analyses revealed that this effect appears to be driven by

325   vocabulary.

326   We are aware of no previous research on imitation abilities of children with reading

327   disability, which was not associated with impaired imitation in the current study. The

328   interesting question raised by the imitation task is whether there is some supramodal imitation

329   ability that affects children's ability to learn language as well as their ability to imitate

330   gestures. Imitation involves perceiving a signal produced by another person and then

331   translating that observed percept into a motor programme for producing the same movement.

332   Without imitation ability, language could not be learned. Insofar as imitation has been an

333   explicit focus of research attention, this has mainly concerned children with autism, rather

334   than SLI. Deficits in imitation are a hallmark of autism, and are thought to be a barrier to

335   learning to communicate. Our results suggest that milder imitative difficulties may underlie

336   slow learning in some children with LI. Nevertheless, we need to be cautious in interpreting

337   this result. The size of the deficit seen in imitation in the LI group was relatively large (Table

338   1.), but the correlational analysis suggested that nevertheless this result may not be robust.

339   When we considered correlations on individual tests across the full range of ability, the only

340   language test to reliably relate to imitation was WASI Vocabulary. Other measures, such as

341   MLU, Sentence Comprehension and Story Comprehension showed inconsistent correlations

342   with the imitation tasks in the two subsets of twins. Three of the measures, NEPSY Oromotor

343   Sequences, Nonword Repetition and Sentence Repetition, involved explicit imitation of

344 speech, yet these subtests were associated with the motor imitation task in only one of the two

345 subsets of twins.

346   Some neurological data supports the link between language and imitation. Repetitive

347 transcranial magnetic stimulation (rTMS) to Broca's area, well known for its role in speech

348 production, interfered with imitation of action (Heiser et al., 2003). The stimulation did not

349 significantly impair production of the same action when the cue to perform was spatial. This

350 specific deficit in action imitation during rTMS suggests that certain parts of Broca's area

351 have a role in action imitation. MRI has shown functional and structural abnormality in

352 children with SLI. Badcock et al. (2012) found reduced activation in Broca's area in children

353 with SLI during an inner speech task, and increased grey matter in this area compared to

354 unaffected siblings and controls. Broca's area could be a shared area involved in both

355 language and imitation ability. Furthermore, fMRI data showed that action observation caused

356 activation in Broca's area (Fadiga et al., 2006). Heiser et al. (2003) described Broca's area as

357 an area of shared neural mechanisms for communication; through language, action imitation,

358 and action recognition.

359 *General Discussion*

360   It is important to note that all of these tasks, even those not considered speeded,

361 included a speed element. The sequence task was scored according to the speed with which

362 children completed 8 sequences. This measure alone cannot tell us whether some children got

363 lower scores because they made sequence errors, or because they were simply slower but

364 accurate. However, as children with reading disability were no slower at repetitive fingertip

365 tapping, it suggests that there was something specific to the sequence tapping beyond speed

366 that caused the increased time score. Similarly, the deficit seen in the peg-moving task may be

367   one of dexterity or sequencing as opposed to speed. Time pressure did not appear to be a

368   major factor affecting performance in the test of imitating hand positions, but nevertheless

369   there was a time limit for each trial, and in future studies it would be worth noting whether

370   some children continued to attempt the posture after the limit expired. We used existing

371   standardized tests, which are not designed to tease apart the individual skills which may be

372   contributing to lower performance. In future work it would be useful to devise tasks which are

373   designed to separate the requirements for imitation, sequence and speed, and to look more

374   directly at motor learning as well as performance.

375   Overall, these results provide further evidence that language and reading impairments

376   co-occur with other deficits, seen here in poor fine motor ability compared to peers. We have

377   also confirmed that children with RD have motor deficits affecting the sequencing of

378   movements even when their oral language skills are intact. In contrast, deficits in imitation of

379   hand positions were selectively associated with oral language difficulties. Our results support

380   the view that RD and LI do not just vary in severity; although they commonly overlap. The

381   distinctive patterns of associated motor impairment suggest we will obtain more coherent

382   results if we assess both oral language and literacy skills when looking for neurobiological

383   bases of these developmental disorders.

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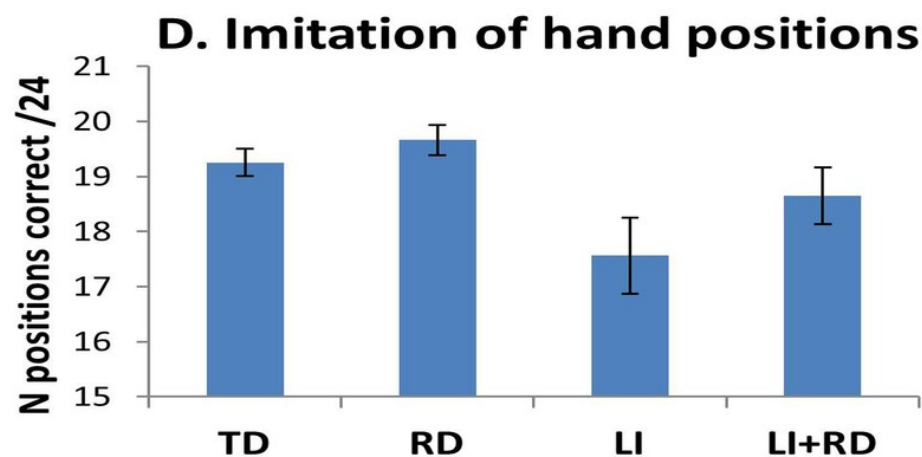
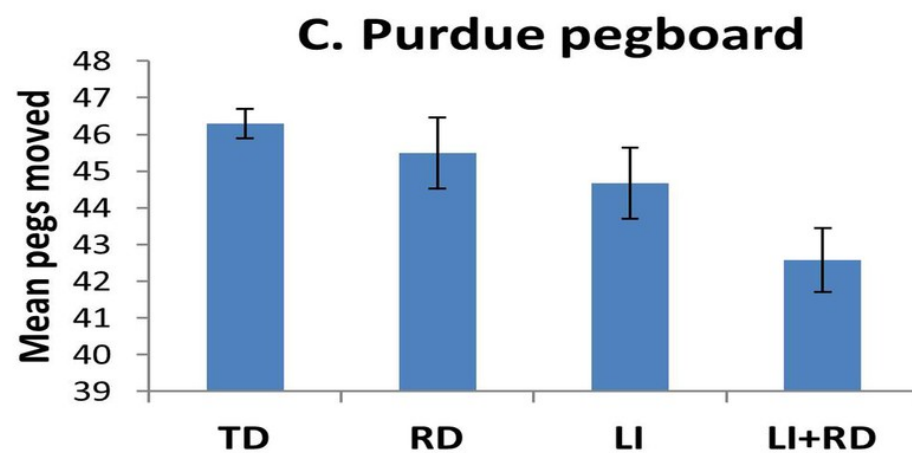
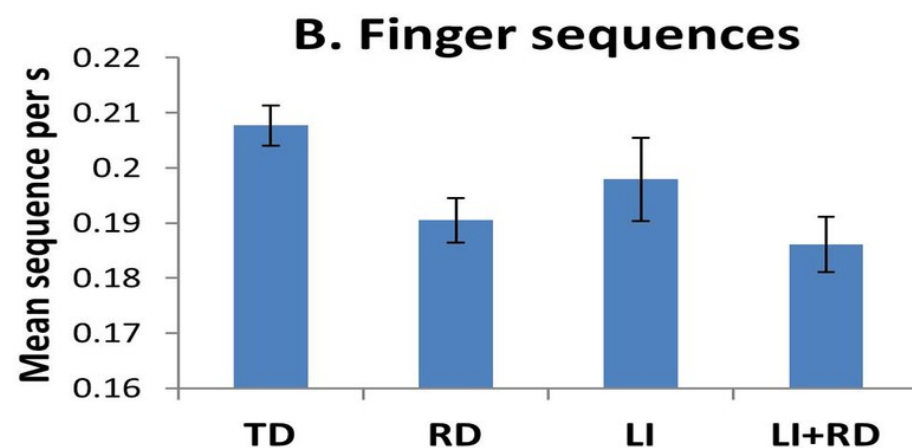
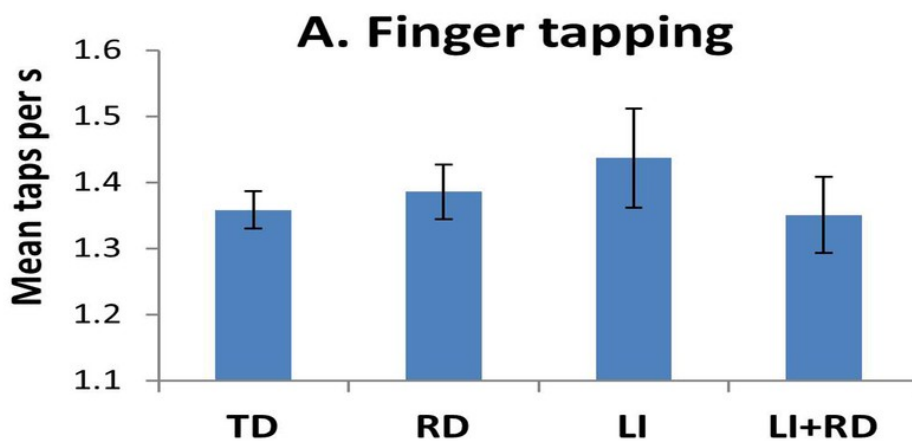
Figure 1

Mean scores on motor tests by group

TD = typically developing; RD = reading disability; LI = language impairment; Error bars show standard errors.

A. Finger tapping

B. Finger sequences

C. Purdue pegboard

D. Imitation of hand positions

F-ratios, p-values and effect sizes for main effects from multilevel model analysis for four motor tasks

Effect	Statistic	Finger tapping	Finger sequences	Purdue pegboard	Imitation of hand positions
LI	F	0.03	0.16	6.94*	8.87*
	p	.860	.688	.009	.003
	Cohen's d	.02	.05	.31	.34
RD	F	0.45	4.01*	3.98*	1.30
	p	.502	.046	.047	.255
	Cohen's d	.07	.21	.21	.12
LI x RD	F	1.70	0.15	0.77	0.94
	p	.193	.694	.381	.332
sex	F	5.45*	1.03	3.16	2.09
	p	.021	.311	.077	.150

Figure 2

Pearson correlations between cognitive measures and motor test scores, separately for twin 1 and twin 2

A correlation of .16 is significant at .05 level; a correlation of .20 is significant at .01 level; a correlation of .26 is significant at .001 level.