

# Implicit motor learning deficits in dyslexic adults

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## Abstract

Children with developmental dyslexia fail to develop age-appropriate reading skills despite adequate intelligence and education. It has been suggested that dyslexics' various literacy, sensory and motor difficulties may be related to impaired cerebellar function. As the cerebellum is involved in motor learning, we measured serial reaction time performance in 40 adults (21 controls, 19 dyslexics). Dyslexic subjects performed comparably to controls during the randomly-ordered reaction time blocks, indicating that the dyslexics were as able as controls to make appropriate stimulus-response associations. However, the dyslexics failed to show the reaction time reduction that the control group showed during the repeated sequences ( $p = 0.018$ ) and there was a significant group by condition effect when comparing the last two blocks of the sequence condition with the first two blocks of the final random condition ( $p = 0.008$ ). Furthermore, there was a significant difference between good and poor readers on the degree of learning during the task ( $p = 0.015$ ). This suggests that some dyslexics may suffer from an implicit motor learning deficit, which could generalize to non-motor learning.

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## 1. Introduction

Developmental dyslexia is currently defined as deficient literacy acquisition despite adequate intellectual ability and sufficient educational provision. The dominant theory of dyslexia proposes that a phonological processing deficit underlies the literacy difficulties experienced by dyslexic individuals (e.g., Ramus, 2004; see also Castles & Coltheart, 2004).

However, many dyslexics also demonstrate motor coordination and balance problems (see Fawcett & Nicolson, 1999), slower information-processing speed (Wolf, 1991; Nicolson & Fawcett, 1994), and low-level visual and auditory processing deficits (see Talcott & Witton, 2002). Stein has proposed that these difficulties may be due to abnormalities in CNS magnocellular systems (Stein & Walsh, 1997; Stein, 2003). Nicolson, Fawcett and Dean (2001) propose that cerebellar dysfunction is the cause of developmental dyslexia. As the magnocellular system projects strongly to the cerebel-

lum, both theories suggest that cerebellar processing may be impaired in dyslexia.

There is ample clinical evidence that the cerebellum is involved in motor learning. Patients with cerebellar pathology have difficulty acquiring classically conditioned responses (for review, Yeo & Hesslow, 1998) and impaired motor learning (Petrosini, Molinari, & Dell'Anna, 1996). Cerebellar patients are impaired in associative learning tasks (see Timmann et al., 2002, 2004) and procedural learning is worse in patients with focal cerebellar lesions (Molinari et al., 1997; Beldarrain, Grafman, Pascual-Leone, & Garcia-Monco, 1999).

Serial reaction time tasks (SRTTs) are often used to measure implicit motor learning (Nissen & Bullemer, 1987). Implicit learning tasks do not require conscious memories of prior events, yet subjects' performance reflects experience acquired during the task. The distributed neural network underlying implicit learning is not fully understood, but the cerebellum is definitely involved. Molinari et al. (1997) and Gomez-Beldarrain, Garcia-Monco, Rubio and Pascual-Leone (1998) both found that patients with cerebellar lesions show impaired implicit learning compared with controls

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and imaging studies have confirmed cerebellar activity during motor sequence learning (Toni, Krams, Turner, & Passingham, 1998; Ungerleider, Doyon, & Karni, 2002).

Kell, Griffiths and Frith (2002) found that both dyslexic and control groups demonstrated some degree of implicit learning in a SRTT. Yet Nicolson et al. (1999) found that there was less cerebellar activation in dyslexic brains while learning a new motor task and Nicolson, Daum, Schugens, Fawcett and Schultz (2002) found that dyslexic adults show abnormal eyeblink conditioning. Also, Vicari, Marotta, Menghini, Molinari and Petrosini (2003) found that dyslexic children show deficient implicit motor learning.

We investigated implicit motor learning using a serial reaction time task in control and dyslexic adults. Our prediction was that, if there is an implicit learning deficit in developmental dyslexics, there should be impaired performance on this task.

## 2. Methods

The project was approved by the Central Oxfordshire Research Ethics Committee (COREC) and all subjects gave their written informed consent to participate in the study.

Twenty-one adult controls (9 male, 12 female) with no neurological or literacy problems and 19 adult dyslexics (9 male, 10 female) took part. Dyslexics had a well documented history of developmental dyslexia independently assessed by an educational psychologist and/or a continuing discrepancy between cognitive and literacy abilities. The groups were matched for age (control mean age 22 years and 10 months; dyslexics 23 years and 11 months) and cognitive ability.

Cognitive function was assessed using the similarities, vocabulary, block design, digit symbol and digit span subtests of the Wechsler Adult Intelligence Scale-Revised (WAIS-R) (Wechsler, 1981). Single-word reading and spelling was measured using the Wide Range Achievement Test (WRAT) (Jastak & Wilkinson, 1984).

Two computerized tests of orthographic and phonological skills were administered. The Olson orthographic test is a two-alternative forced-choice word-pseudohomophone discrimination task (Olson, Forsberg, Wise, & Rack, 1994), presented using SuperlabPro (version 1.04, Cedrus). Two versions of a word (one a real word, e.g. 'rain'; the other a pseudohomophone, 'rane') were presented side by side on a computer screen. Subjects indicated which was spelled properly. Feedback ('correct' or 'incorrect') was given after each trial. Eight practice items were followed by 80 experimental items. Accuracy and reaction times (RTs) were calculated. Similar software and procedure were used for the phonological choice task. Three non-words were presented and the subject decided which sounded like a real word (e.g., *nite dite hote*; 'nite' sounds like 'night'). There were five practice and 60 experimental trials.

The serial reaction time task (SRTT) was based on Nissen and Bullemer (1987). It was run on a computer using SuperLabPro software. Subjects were asked to press the button box button that corresponded to a particular number (1–4) that appeared on the screen as quickly and accurately as possible. The numbers always appeared such that '1' was leftmost, and '2', '3' and '4' appeared from left to right across the screen. Both numeric and a positional cues were used because a combined set of cues has been found to increase implicit learning (Robertson & Pascual-Leone, 2001), and thus the length of the experiment could be shortened.

Three blocks of trials were run: first a block of 100 randomly ordered trials; then 100 consisting of 10 repetitions of a 10-item sequence (4321342312); followed by a further block of 100 random trials. The stimulus remained on the screen until the subject responded correctly. The inter-stimulus interval was 400 ms. To assess explicit learning of the sequence, subjects were asked: "Did you notice anything different about the tasks?" "Did any button presses seem to come together tasks?" "Was there a pattern or sequence present tasks?"

Data analyses were performed using SPSS version 12.0. Reaction time data was log transformed prior to analysis to allow for parametric statistical analysis.

## 3. Results

Table 1 shows the ANOVA results comparing the groups' cognitive and literacy scores. Dyslexic subjects performed significantly worse on digit span, reading, spelling, orthographic choice reaction time and phonological choice accuracy. The lack of group difference on the orthographic choice task accuracy is likely due to the subject population (university students) and indicates a well-compensated dyslexic group.

Table 2 shows the results of the performance of the serial reaction time task by group. Dyslexics performed comparably to the control group in accuracy and reaction time on the random blocks; the groups showed no reaction time differences when the button presses were randomly ordered. However, the dyslexics were significantly slower during the 2nd, 6th, 9th, and 10th repeated sequence blocks ( $p=0.044$ , 0.032, 0.017, 0.014, respectively) showing less implicit motor learning of the repeated sequence. Only two subjects (both controls) demonstrated awareness of any pattern to the button presses; but neither could explicitly name any part of the sequence. While 18 of the 21 control subjects (86%) showed evidence of implicit motor learning (as measured by a greater than 10% increase in reaction times between the final repeated sequence block and subsequent random block), only 8 of the 19 dyslexic subjects (42%) did.

A repeated measures ANOVA showed a significant group by condition interaction during the random and repeated sequence blocks ( $p=0.03$ ). Given the effects of learning are only evident in the final blocks of the repeated sequence condition, we entered the last two blocks of the sequence

Table 1  
Cognitive and literacy scores

Task	Control	Range	Dyslexic	Range	<i>p</i> -Value
Cog	13.2 ± 1.1	10.75–15.0	13.3 ± 1.8	10.2–16.5	n.s.
Digit span	13.5 ± 3.2	6.0–18.0	8.8 ± 2.7	5.0–15.0	<0.001**
Reading	117.2 ± 5.1	107–126	105.5 ± 7.0	91–115	<0.001**
Spelling	116.2 ± 5.9	105–128	98.3 ± 14.4	51–114	<0.001**
Orth %	96.5 ± 4.7	79–100	93.7 ± 4.3	86.2–100	n.s.
Orth RT	802.7 ± 124.5	644.9–1104.4	1154.8 ± 1121.0	624.0–5634.0	0.003**
Phon %	91.6 ± 6.4	78.3–100	86.1 ± 9.1	63.3–100	0.045*
Phon RT	3058.3 ± 952.2	1045.7–4503.7	3330.4 ± 1280.9	2180.0–8552.2	n.s.

Scores = mean ± S.D.; Cog = WAIS mean of similarities, block design, vocabulary, digit symbol, picture arrangement; reading, spelling = WRAT reading and spelling; Orth% = % correct, orthographic choice task; Orth RT = reaction time (ms), orthographic choice; Phon% = % correct, phonological choice task; PhonRT = reaction time (ms), phonological choice. WAIS scores = mean of 10, S.D. 3; WRAT scores = mean of 100, S.D. 15. n.s., *p* > 0.05.

Table 2  
SRTT performance by group

	Control	Range	Dyslexic	Range	<i>p</i> -Value
Errors	18.4 ± 11.5	3–50	20.8 ± 13.1	6–45	n.s.
Random 1–10	411.1 ± 63.9	320.2–527.5	453.7 ± 161.5	320.4–1019.5	n.s.
Sequence 1–5	377.7 ± 64.0	275.0–521.2	431.9 ± 111.2	300.4–758.7	(0.059)
Sequence 6–10	335.3 ± 63.4	214.5–479.2	401.7 ± 113.4	259.2–665.9	0.018*
Random 11–20	398.4 ± 52.4	312.5–512.1	434.2 ± 82.1	320.7–633.7	n.s.

Scores = mean ± S.D.; RT = reaction time (ms). n.s., *p* > 0.05, one-way ANOVA. Values in parentheses approach significance.

condition and the first two blocks of the subsequent random condition into a repeated measures ANOVA, which increased the significance of the group by condition interaction (*p* = 0.008).

To investigate how good versus poor readers performed, we split the group based on the median literacy score. There were significant differences both on the reaction times during the sixth to 10th repeated sequence blocks (*p* = 0.010, poor readers were slower) and the percent increase in reaction time between the final sequence and subsequent random block (*p* = 0.015, greater learning in good readers).

#### 4. Discussion

Our results show significant differences in implicit motor learning between good and poor readers. Dyslexics showed less decrease in reaction times during the repeated sequence, whereas during the randomly ordered trials their reaction times were comparable to the control group. However, not all the dyslexics had difficulties with this task, which may reflect the high level of ability in this particular dyslexic group as well as the general heterogeneity of deficits found in dyslexia.

Our results contrast with Kell et al. (2002) who found that both dyslexic and control groups demonstrated implicit learning on a serial reaction time task. However, in their study control subjects showed recognition of one of the sequences presented, but the dyslexics did not. Thus, the sequence may have become explicit for the controls but not for the dyslexics, suggesting that there were learning differences between the groups. Our data in a similar group of subjects (adult uni-

versity students) indicates that some dyslexics are impaired on this task.

Our results do not necessarily imply that the cerebellum is involved in the learning aspect of the SRTT, or that dyslexic subjects who show implicit learning deficits necessarily have cerebellar dysfunction. Seidler et al. (2002) have argued that the cerebellum may simply be involved in the expression of motor learning, e.g., the modification of performance. However, reaction times during the random condition in the adult group were the same in both dyslexics and controls, while the repeated sequence reaction times were not. This implies that, regardless of whether the cerebellum is involved in the learning of the sequence or the modification of performance, the dyslexic group underperformed during the repeated sequence condition. In addition to the cerebellum, many distributed brain regions are likely involved in implicit learning, including the prefrontal cortex and basal ganglia (Pascual-Leone, Wassermann, Grafman, & Hallett, 1996; Peigneux et al., 2000); therefore, we can only suggest that this system, which includes the cerebellum, is not functioning optimally in dyslexic individuals.

It may be possible that the difference between the dyslexics and controls is not due to implicit learning deficit per se, but due to differences in ‘cognitive load’; dyslexics may need to concentrate more to make the stimulus-response associations, and thus are not able to capitalize on the sequence cues within the repeated sequence block. Whether or not this inability to automatize stimulus-response codes is due to cerebellar dysfunction (Nicolson et al., 2001) remains to be seen.

These preliminary results indicate that some dyslexics do not show learning during the serial reaction time task. Given

the proposed role of the cerebellum in this task, and previous evidence of cerebellar dysfunction in dyslexia, this suggests that the cerebellum may be part of the disrupted neural circuitry in dyslexia. Further work is necessary to determine whether dyslexics suffer from a general deficit in implicit learning; such a deficit could contribute to the laborious learning often seen in dyslexic children, rendering them unable to capitalize on the subtle cues that enable rapid learning. Karmiloff-Smith (1992) suggested that cognitive development relies on procedural learning to begin the initial phase of setting up a new stage of representation. A deficit could inhibit new skill acquisition, which would impact greatly on learning to read due to the complexity of the task demands. There were significant implicit learning differences between the good and poor readers, suggesting that there may be differences in poor readers' ability to extract cues from the environment that aid literacy acquisition.

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