Comparison of Deficits in Cognitive and Motor Skills among Children with Dyslexia

Roderick I. Nicolson and Angela J. Fawcett

University of Sheffield
Sheffield, England

There is a growing body of evidence that children with dyslexia have problems not just in reading but in a range of skills including several unrelated to reading. In an attempt to compare the severity and incidence of deficits across these varied domains, children with dyslexia (mean ages 8, 12, and 16 years), and control groups of normally achieving children matched for IQ and for age or reading age, were tested on a range of primitive (basic) skills. The children with dyslexia performed significantly worse than the same-age controls on most tasks, and significantly worse even than the reading-age controls on phoneme segmentation, picture naming speed, word tachistoscopic word recognition, speeded bead threading and some balance tasks. The overall performance of the children with dyslexia is interpreted as showing less complete automatization than normal.

One of the fascinations of dyslexia for researchers is that, whatever one's interest in human behavior and performance, children with dyslexia will obligingly show interestingly abnormal behavior in precisely that behavior. Early pioneers in dyslexia research, including Morgan, Hinshelwood, and Orton, believed that visual problems underlay the apparent "word blindness"

Annals of Dyslexia, Vol. 44, 1994

ISSN 0736-9387

and Orton introduced the term *strephosymbolia* to indicate that, although he believed the problem to be primarily visual, it was not one of blindness per se, but one of "twisted symbols," a difficulty in distinguishing the order of letters. Around 20 years ago, there was a gradual realization that problems of language must, at least in part, be responsible for the reading deficits (Vellutino 1979). This general hypothesis has been refined over the years (Miles 1983; Snowling et al. 1986; Stanovich 1988) to provide what is arguably the consensus theoretical belief of most dyslexia researchers with a background in psychology, namely that children with dyslexia suffer from an early impairment in their phonological skills, and this impairment prevents them from acquiring the word decoding and blending skills necessary for normal acquisition of the skill of reading.

However, it is by no means clear that skill deficits are restricted to the phonological domain. Many parents of children with dyslexia recall that their children were unusual in their early years—slow to walk, slow to talk, rather clumsy, maybe a bit accident prone. These anecdotal reports were distilled by the late Jean Augur into a set of 21 key points (Augur 1985). As expected many of her points reflected lack of phonological skill. Equally notable, however, were consistent problems with motor skill. Indeed, motor skill problems accounted for Augur's first five points, together with "Difficulty carrying out more than one instruction at a time" and "Excessive tiredness due to amount of concentration and effort required." More formal analyses of motor skill were performed by Rudel (1985) who concluded that *"There is evidence of early difficulties in newly acquired [motor] skills, but these difficulties are largely outgrown by 9-10 years."* A particularly large study was reported by Haslum (1989), as part of the British National Cohort study in which 12,905 children were followed from birth to ten years, with a systematic series of tests being conducted at birth and at 5 and 10 years of age. As part of the testing procedure for the ten-year-old children, selected items of the Bangor Dyslexia Test (Miles 1983, 1993) were administered, allowing children with dyslexia to be identified, and thereby allowing analysis of those factors that were highly associated with dyslexia at birth, five years and ten years of age. In brief, the tests that correlated most highly with dyslexia were: balancing on one leg, walking backwards, sorting matches, and a "graphaesthetic" task (identifying by touch a shape traced on the back of the hand); together with family history, birth history, and childhood diseases. A recent series of studies by Wolff (1990) has shown persistent problems in tapping rhythm for children with dyslexia, specifically when asked to tap the hands asynchronously.

By contrast to this behavioral and observational work, many American researchers have studied the underlying neural substrate. Again, dyslexia has provided intriguing abnormalities. Large scale twin and familial studies (e.g., Smith et al. 1983) established specific abnormalities both of chromosome 15 and, more recently, chromosome 6 (Lubs et al. 1991). Studies of brain electrical activity in response to different types of stimulus have shown abnormalities for the processing of linguistic stimuli (Duffy et al. 1980). Magnetic resonance studies (Hynd et al. 1990; Leonard et al. 1993) revealed morphological differences including fascinating indications of differences in symmetry in the planum temporale and other brain regions. Most directly, comparative neuroanatomical studies of dyslexic brains (Galaburda, Rosen, and Sherman 1989) have established *". . . a uniform absence of left-right asymmetry in the language area and focal dysgenesis referrable to midgestation . . . possibly having widespread cytoarchitectonic and connectional repercussions. . . . Both types of changes in the male brains are associated with increased numbers of neurons and connections and qualitatively different patterns of cellular architecture and connections"* (p. 383).

In a promising potential link between speed of processing, neuroanatomical abnormalities, and dyslexia, anomalies have been identified in rapid visual processing. For instance, Lovegrove and his colleagues (e.g., 1990) demonstrated that children with dyslexia had impaired sensitivity for detecting flicker. Furthermore, this deficit has now been linked to neuroanatomical abnormalities in the magnocellular pathway linking the eye to the visual cortex via the lateral geniculate nucleus (Livingstone et al. 1991). Visual deficits have also been identified by Stein and his colleagues (e.g., 1989). Other dyslexia research has established problems more generally in rapid performance. Denckla and Rudel (1976) discovered problems in rapid automatized naming of successive stimuli (including non-linguistic stimuli such as colors); Tallal (1984) identified impairments in recalling the order of rapidly presented temporal events; and Wolf (1991) reported that early deficits in naming speed for letters and numbers predicted later deficits in reading, with a direct relationship between the speed deficit and the severity of the reading impairment. More recently, Nicolson and Fawcett (1994) have demonstrated reduced speed of lexical access, and even of selective choice reaction to one of two pure tones, whereas simple reaction to that tone was normal.

In other research we have adopted a learning, or skill acquisition, perspective. It is evident that such a perspective should be of use in analyses of reading problems. Consider the conclusions of a recent detailed overview and analysis of the teaching of reading: "*. . . Laboratory research indicates that the most critical factor beneath fluent word reading is the ability to recognize letters, spelling patterns, and whole words effortlessly, automatically and visually. The central goal of all reading instruction—comprehension—depends critically on this ability.*" (Adams 1990, p. 54). The reason that theorists have not seriously considered learning as a viable framework is that it fails to explain the apparent specificity of the deficits in dyslexia (Stanovich 1988). If they have a general problem in learning, why do children with dyslexia not show problems in *all* skills, cognitive and motor? In our approach to this difficulty we were encouraged first by the observation that, whatever skill theorists had examined carefully, a deficit had been observed in children with dyslexia. Furthermore, careful observation of children with dyslexia suggests that, although they appear to be behaving normally, they show unusual lapses of concentration and get tired more quickly than normal when performing a skill (Augur 1985). In the words of the parent of one of our subjects, life for a child with dyslexia might be like living in a foreign country, where it is possible to get by adequately, but only at the expense of continual concentration and effort. One of the key concepts in skill acquisition is automatization—the process by which skilled performance becomes smoother and smoother, requiring less and less effort, following extensive practice (Fitts and Posner 1967; Shiffrin and Schneider 1977; Anderson 1982). This belief in a learning deficit led us (Nicolson and Fawcett 1990) to formulate and test two linked hypotheses: first, the Dyslexic Automatization Deficit (DAD) hypothesis, that children with dyslexia have unusual difficulty in automatizing any skill, whether motor or cognitive, and second, the Conscious Compensation (CC) hypothesis, namely that children with dyslexia are normally able to overcome their automatization deficit by means of consciously compensating for it, that is, by trying harder and/or by using strategies to minimize or mask the deficit.

In a rigorous test of the DAD/CC hypothesis, we investigated motor skill, and in particular the gross motor skill of balance, on the basis that this was one of the most highly practiced of all skills, with absolutely no linguistic involvement. Details of the study are provided in Nicolson and Fawcett (1990). Our subjects were 23 children with dyslexia around 13 years old and 8 normally achieving children, with groups matched overall for age and IQ. We monitored their performance for three tasks: standing on both feet (one foot directly in front of the other); standing on one foot; and walking. All three tasks took place on a low 'beam' four inches high and four inches across, made of large plastic bricks. Balance performance was determined by videotaping each session, with separate cameras for hands and feet, and subsequently scoring each session for wobbles, assigning a half point for a small wobble (10-20°), one point for a medium wobble (20-50°) and two points for a major wobble (overbalancing or putting one foot down). Scoring was independently checked by a scorer blind to the identity of each subject. The balance tasks were performed under two conditions: single task balance, in which the subjects had merely to balance; and dual task balance, in which they had to balance while undertaking a further secondary task. Two secondary tasks were used: either counting or performing a choice reaction task. Each secondary task was initially calibrated so as to be of equivalent difficulty for each subject, by adjusting the task difficulty (for counting) or by providing extended training (for choice reactions) so that, under "just counting" or "just choice reaction" conditions all subjects fell into the same performance band. The results were exactly as predicted by DAD/CC. Under single task balance conditions there was no difference in balance between the groups. Under dual task conditions the children with dyslexia showed a highly significant impairment in balance, whereas the control children showed no deficit. Even more convincing, in addition to the significant differences at the group level, the pattern of performance also applied to almost all the individuals, with 22 out of the 23 children with dyslexia showing a decrement under dual task conditions whereas most of the controls actually improved (owing, no doubt, to the effect of practice). More recently we have extended these findings, obtaining qualitatively similar results with younger children with dyslexia and also with blindfold balance replacing the dual task balance (Fawcett and Nicolson 1992).

It is clear, therefore, that researchers from different backgrounds have identified a range of apparently unrelated problems in dyslexia. Faced by the diversity of deficits in dyslexia, it is natural to say to oneself "They can't all be right can they? What is the deficit *really*? Is the phonological, visual, processing speed or motor skill deficit the primary one?" Following the prescription of the late Allen Newell in his influential analysis of how one might make progress in complex domains (1973) we decided to mount an interdisciplinary attack on dyslexia, attempting to characterize performance on the entire range of skill (even skills that were thought to be unaffected by dyslexia). In this way we hoped to be able to build an overall picture of the pattern of difficulties associated with dyslexia, constructing a corpus of data that would be useful to all theorists.

The Research Program

Subjects

For subject selection, we used the standard exclusionary criterion of "children of normal or above normal IQ, operationalized as IQ of 90 or more on the WISC-R (Wechsler 1976), without known primary emotional, behavioral or socioeconomic problems, whose reading age (RA) was at least 18 months behind their chronological age (CA)." We recruited three groups of children with dyslexia, mean ages 16, 12, and 8 years[1], together with three groups of normally achieving children matched for age and IQ. This gave us six groups, D16, D12, and D8; and C16, C12, and C8 for the three age groups of dyslexic and control children respectively. The extensive empirical research program took place over a period of around one year. The four older groups were recruited first, and the 8-year-old groups were added later. Consequently the mean age of the four older groups increased by about one year from start to end of the research program, whereas that of the 8-year olds increased by only a few months. Psychometric details at the start of testing are given in table 1. It should also be noted that the numbers of subjects participating in each experiment fluctuated somewhat according to availability at the various testing periods. This three-age-group design allows performance to be compared with children of the same age (D16 vs C16, D12 vs C12; D8 vs C8), children of around the same reading age (D16 vs C12; D12 vs C8) and children of around half the age (D16 vs C8).

Skill Tests

Next we designed a variety of tests intended to tap performance on "primitive" cognitive and motor skills, that is, basic skills that form the building blocks for more complex skills in

[1]The children with dyslexia were located via the local Dyslexia Institute or the local branch of the British Dyslexia Association. Other than checking that the children met our criteria for dyslexia, and that they were willing to undertake testing on a long-term basis, no screening or selection whatsoever was undertaken. Subjects were paid around $5 per hour, and participated with fully informed consent.

Table 1
Psychometric Data for the Six Groups of Subjects

The groups of children with dyslexia are labeled D16, D12, and D8, with the suffix indicating the mean age. Similarly the groups of normally achieving children are labeled C16, C12, and C8. The mean value for each group is presented first, with the range of values bracketed below.

	D8	C8	D12	C12	D16	C16
N	12	10	10	11	13 {11}[b]	12
IQ (WISC-R)	113.4	115.1	111.2	111.6	105.0	106.8
	[96-133]	[101-133]	[101-128]	[96-129]	[88-126]	[92-130]
					{105.0 [92-126]}[b]	
Chronological Age	8.7	8.2	12.3	12.4	16.3	16.4
	[7:7–9:9]	[7:0-8:8]	[10:7-13:9]	[12:0-13:3]	[15:0-17:2]	[16:0-16:9]
Reading Age	6.6	9.2	9.3	12.5	11.9	15.0[a]
	[5.5-7.9]	[7.7-11.1]	[7.4-11.6]	[11.8-13.4]	[8.1-14.4]	[14.8-15.0]
					{12.5 [10.4-14.4]}[b]	
Spelling Age	5.6	7.1	6.8	11.8	9.0	14.9
	[5.0-6.7]	[6.0-8.6]	[5.0-9.0]	[10.6-12.7]	[6.0-13.0]	[14.1-15.9]

[a]Fifteen represents ceiling on the Schonell test of reading age used. All this group were reading at this level, and the majority had reached this level at around the age of 15.

[b]In order to improve the overall between-groups match for reading age (RA) for D16 and C12 two D16 subjects were omitted from the RA inferential analyses. RA analyses with or without these two subjects gave very similar significance levels. Figures in {brackets} show the psychometric data excluding these subjects.

each domain. Wherever possible these tests were implemented on the Apple Macintosh computer using digitized sound for instructions and stimuli and using automatic event recording and data analysis in order to standardize testing techniques and to facilitate replication by other researchers. In addition to psychometric tests, four generic types of test were used, namely tests of phonological skill, working memory, information processing speed, and motor skill. The psychometric tests used the WISC-R scales (Wechsler 1976), with spelling age and reading age based on the Schonell tests of single-word reading and spelling. The tests of phonological skill included phonological discrimination ability for phonologically confusable stimuli (Bishop 1985), in which pairs of words such as "fuse" and "views" are presented, and the subject has to judge whether the two stimuli are the same or different; segmentation ability (Rosner and Simon 1971), in which the subject has to be able to break down a word into its phonemes (starting with easier tasks such as "say 'cowboy' without the 'cow,'" and moving to more difficult ones such as "say 'smack' without the '/m/'"); and rhyme / sound categorization ability (a simplified version of the tests used in Bradley and Bryant 1983) for phonemes at the beginning and end of words, with representative questions being "does *cat* rhyme with *map*?" and "do *map* and *man* start with the same sound?" The working memory tests included nonword repetition (Gathercole and Baddeley 1990) in which the subject has to repeat a nonsense word immediately after hearing it, with stimuli taken from a set of 40 ranging from two to five syllables (including *bannow* and *versitrationist*), the mean Memory Span for words of one, two and three syllables (measured as the longest list of words that the subject can recall in the correct order), and articulation rate (the mean time to repeat five times *bus*, *monkey*, and *butterfly*), which is included in this category because memory span and articulation rate are known to co-vary (Baddeley, Thomson, and Buchanan 1975). Tests of information processing speed included: tests of speed in naming simple outline pictures (such as an outline of a cat), primary colors, single digits, and single lower case letters (all presented unpaced); simple reaction to a pure tone (press the button as soon as you hear the tone) and selective choice reaction time to pure tones (press the button for the low tone, ignore the high tone); visual search (locating a distinctive spotty dog on each of several crowded pages in a child's puzzle book), and tachistoscopic word recognition on a graded series of words presented for gradually decreasing times (Word Flash). The motor skill tests included tests of bead threading (how many beads can be threaded in one minute) and pegboard peg moving (the time to move a row of ten pegs to the next row of a pegboard) together with a variety of static balance tasks. These included standing on both feet, standing on one foot, standing on both feet when blindfolded, and standing on one foot while blindfolded, and dual task balance, which involved standing on one (or two) feet while undertaking a secondary, choice reaction, task. The dependent variable for the balance tasks was the number of wobbles occurring within one minute (30 seconds for one foot balance). The computer-based versions of all the tests are available in the COMB set (Nicolson 1993).

Results

Detailed presentations of results and procedures for the different types of skill are given in Fawcett and Nicolson (1994 a, b, c). The mean and standard deviation for the psychometric tests are presented in table 1: results on measures assessing basic skills are collated in table 2. Results of inferential tests are collated in tables 3 and 4. Among the control groups, older subjects (C16) performed significantly better than younger subjects (C8) on the following measures; reading, phonological discrimination and segmentation, memory, speed of articulation, speed of processing, and single task balance. Older and younger controls were roughly equivalent on fine motor skill (beads and pegs) and on the rhyming measures. In other words, the results for control groups are largely as one would expect, with some of the skills still developing in the teens, and some (such as the beads test and the rhyming test) already at ceiling (at least on the tests used).

As is evident in table 1, the dyslexic subjects were well matched with controls on age and IQ, but differed dramatically in reading level: it is notable that the older the dyslexic, the more reading age lagged behind chronological age. In terms of reading level, the 16-year-old children with dyslexia were comparable to the 12-year-old controls, and the 12-year-old children with dyslexia were comparable with the 8-year-old controls. As expected from the literature (e.g., Thomson 1984), the deficit in spelling was even greater than for reading. Consistent with these differences in their reading, but in contrast to their comparability in terms of age and IQ, there were significant differences between children with dyslexia and their CA controls on all but two of the 22 measures presented. Only on the simple reaction time measures did children with dyslexia consistently perform at normal standards on all three age levels. (Differences on the memory task failed to reach significance, but there was a trend towards memory weaknesses in the dyslexic groups.)

In comparison with CA matched controls, dyslexic subjects showed marked deficits in all measures of phonological skill. On the phoneme segmentation task, older dyslexic subjects also performed more poorly than RA controls. The performance of the D16 group was surprisingly poor, as they did not score even as well as the C8 group, although this difference was not significant. For memory, articulation, and most measures of processing speed, although the D8 group again showed severe impairments relative to C8 controls, the older dyslexic groups did not perform nearly as poorly relative to CA matched control groups. Of these processing speed measures, the children with dyslexia performed less well than RA controls only on picture naming and word flash: otherwise, the D16 group consistently (if not significantly) outperformed at least the C8 group.

In comparing children with dyslexia and controls, the most notable result was the extraordinarily poor performance of all

Table II
Summary of Mean Scores for each Group on each Test
(Standard deviations are given in parentheses). Times are given in seconds.

	D8	C8	D12	C12	D16	C16
Spelling Age (years)	5.59 (0.63)	7.13 (1.05)	6.82 (1.60)	11.8 (0.78)	9.03 (2.36)	14.9 (0.57)
Phonological Discrimination %	78.4 (4.59)	82.1 (4.41)	80.9 (6.95)	87.7 (4.64)	85.1 (2.89)	88.3 (3.80)
Rhyme %	91.0 (9.23)	98.0 (3.57)	94.7 (3.74)	98.0 (2.63)	94.0 (6.97)	100 (0.00)
Segmentation %	58.0 (31.4)	83.9 (9.20)	74.7 (14.2)	96.2 (5.15)	80.0 (16.4)	100 (0.00)
Articulation Time (s)	0.62 (0.13)	0.47 (0.05)	0.49 (0.20)	0.36 (0.04)	0.40 (0.09)	0.34 (0.06)
Nonword Repetition %	73.9 (14.7)	85.6 (5.83)	81.8 (10.8)	82.5 (11.2)	93.8 (4.66)	97.1 (4.98)
Memory Span	3.97 (0.69)	4.24 (0.48)	4.40 (0.26)	4.62 (0.59)	4.70 (0.71)	5.08 (0.57)
Word Flash %	76.3 (18.1)	91.3 (2.40)	84.3 (12.2)	94.3 (0.73)	91.8 (3.60)	94.3 (1.18)
Visual Search (s)	22.7 (12.5)	13.5 (6.48)	13.3 (7.70)	8.58 (4.02)	9.41 (3.99)	6.47 (3.12)
Picture Naming (s)	0.85 (0.24)	0.66 (0.08)	0.75 (0.12)	0.57 (0.06)	0.64 (0.08)	0.58 (0.06)
Color Naming (s)	0.68 (0.09)	0.56 (0.13)	0.56 (0.11)	0.44 (0.06)	0.49 (0.07)	0.45 (0.04)
Digit naming (s)	0.68 (0.09)	0.51 (0.08)	0.56 (0.11)	0.45 (0.07)	0.47 (0.07)	0.44 (0.04)
Letter Naming (s)	0.81 (0.16)	0.56 (0.09)	0.63 (0.09)	0.49 (0.07)	0.54 (0.06)	0.46 (0.05)
Letter Naming %	86.1 (14.6)	100 (0.00)	95.3 (6.04)	100 (0.00)	96.9 (7.69)	100 (0.00)
Simple RT (s)	0.43 (0.10)	0.40 (0.08)	0.32 (0.06)	0.33 (0.06)	0.25 (0.03)	0.24 (0.03)
Selective CRT (s)	0.74 (0.32)	0.61 (0.17)	0.58 (0.21)	0.47 (0.07)	0.45 (0.12)	0.32 (0.07)
Beads (no. threaded)	9.17 (2.79)	12.0 (1.22)	9.00 (2.39)	11.9 (2.92)	10.3 (2.09)	11.3 (2.65)
Pegs (s)	14.1 (2.82)	10.5 (1.29)	11.9 (3.25)	9.77 (1.80)	10.2 (1.02)	9.42 (1.18)
Balance errors 2 Feet	14.0 (12.3)	5.44 (4.83)	3.59 (3.07)	2.91 (2.43)	2.57 (1.76)	2.95 (1.73)
Balance errors 2 Feet Blindfold	31.4 (22.5)	6.41 (5.50)	7.86 (5.25)	3.57 (3.99)	6.14 (3.88)	4.43 (2.38)
Balance errors 1 Foot	20.8 (7.63)	9.98 (3.68)	9.59 (4.39)	3.09 (1.70)	7.20 (3.87)	5.31 (1.82)
Balance errors 1 Foot Blindfold	41.0 (9.93)	22.2 (7.28)	28.7 (6.38)	10.2 (2.90)	24.7 (10.0)	14.5 (6.57)
Balance errors Dual	27.0 (13.5)	11.8 (5.76)	12.0 (6.79)	1.74 (0.60)	16.7 (12.9)	3.85 (4.56)

Table III
Summary of Inferential Statistics for Chronological Age and Dyslexia
Groups included were D8, C8; D12, C12; and D16, C16; leading to the factors: 'Dyslexia' with levels Dyslexia and chronological matched Control; and 'Age' with levels 8, 12, and 16 years.

Task	Dyslexia	Age	Interaction
Spelling	$F(1,60)=125, p<.0001$	$F(2,60)=79.2, p<.0001$	$F(2,60)=12.2, p<.0001$
Phon. Discrimin'n	$F(1,60)=15.8, p<.001$	$F(2,60)=10.8, p<.0001$	$F(2,60)=1.0$, NS
Rhyme	$F(1,60)=21.5, p<.0001$	$F(2,60)=2.1$, NS	$F(2,60)=1.3$, NS
Segmentation	$F(1,60)=33.5, p<.0001$	$F(2,60)=6.2, p<.01$	$F(2,60)=1.0$, NS
Articulation Time	$F(1,60)=13.6, p<.001$	$F(2,60)=5.3, p<.01$	$F(2,60)=2.6$, NS
Nonword Rep't'n	$F(1,60)=5.5, p<.05$	$F(2,60)=21.4, p<.0001$	$F(2,60)=2.2$, NS
Memory Span	$F(1,60)=3.8, p<.10$	$F(2,60)=9.7, p<.001$	$F(2,60)=0.1$, NS
Word Flash	$F(1,50)=20.3, p<.0001$	$F(2,50)=7.0, p<.01$	$F(2,50)=3.3, p<.05$
Visual Search	$F(1,49)=10.5, p<.01$	$F(2,49)=12.2, p<.0001$	$F(2,49)=1.1$, NS
Picture Naming	$F(1,61)=20.5, p<.0001$	$F(2,61)=8.7, p<.001$	$F(2,61)=1.8$, NS
Color Naming	$F(1,61)=16.9, p<.0001$	$F(2,61)=14.7, p<.0001$	$F(2,61)=1.3$, NS
Digit naming	$F(1,61)=32.7, p<.0001$	$F(2,61)=21.6, p<.0001$	$F(2,61)=5.1, p<.01$
Letter Naming	$F(1,61)=45.5, p<.0001$	$F(2,61)=25.5, p<.0001$	$F(2,61)=5.6, p<.01$
Letter Naming %	$F(1,61)=11.5, p<.01$	$F(2,61)=2.2$, NS	$F(2,61)=2.2$, NS
Simple RT	$F(1,60)=0.4$, NS	$F(2,60)=42.1, p<.0001$	$F(2,60)=0.1$, NS
Selective CRT	$F(1,60)=8.2, p<.01$	$F(2,60)=15.1, p<.0001$	$F(2,60)=0.1$, NS
Beads	$F(1,56)=14.2, p<.001$	$F(2,56)=0.1$, NS	$F(2,56)=1.4$, NS
Pegs	$F(1,57)=24.4, p<.0001$	$F(2,57)=10.8, p<.0001$	$F(2,57)=3.8, p<.05$
Balance 2 Feet	$F(1,57)=4.8, p<.05$	$F(2,57)=10.0, p<.001$	$F(2,57)=4.0, p<.05$
Balance 2 Feet Blindfold	$F(1,57)=18.7, p<.0001$	$F(2,57)=12.7, p<.0001$	$F(2,57)=8.7, p<.00$
Balance 1 Foot	$F(1,56)=34.7, p<.0001$	$F(2,56)=28.4, p<.0001$	$F(2,57)=5.4, p<.01$
Balance 1 Foot Blindfold	$F(1,56)=64.7, p<.0001$	$F(2,56)=15.4, p<.0001$	$F(2,56)=2.1$, NS
Balance Dual	$F(1,60)=31.5, p<.0001$	$F(2,60)=9.7, p<.001$	$F(2,60)=0.4$, NS

three dyslexic groups on the motor skill tasks, especially bead threading and two balance tasks (blindfold and dual balance). On all three tests of motor skill, the dyslexic groups were not only worse than CA controls, they also performed less well than younger RA controls. Indeed, despite the advantage of eight years experience, the oldest children with dyslexia had not advanced significantly beyond the performance of the very youngest controls on these three motor tasks.

Before attempting a theoretical interpretation of these results, it is important to attempt to characterize them, so as to provide a set of requirements for theorists wishing to develop their own accounts of the data.

Table IV
Summary of Inferential Statistics for Reading Age and Dyslexia
Groups included were D12, C8; and D16, C12; leading to factors: 'Dyslexia' with levels Dyslexia and reading-aged matched Control; 'Reading Age' with levels 8 and 12 years

Task	Dyslexia	Reading Age	Interaction
Spelling	$F(1,41)=8.6, p<.01$	$F(1,41)=42.3, p<.0001$	$F(1,41)=5.5, p<.05$
Phon. Discriminat'n	$F(1,41)=1.7$, NS	$F(1,41)=11.2, p<.01$	$F(1,41)=0.2$, NS
Rhyme	$F(1,38)=3.8, p<.10$	$F(1,38)=0.0$, NS	$F(1,38)=0.0$, NS
Segmentation	$F(1,38)=18.2, p<.00$	$F(1,38)=9.0, p<.01$	$F(1,38)=1.6$, NS
Articulation Time	$F(1,41)=2.0$, NS	$F(1,41)=2.5$, NS	$F(1,41)=2.5$, NS
Nonword Rep't'n	$F(1,41)=2.3$, NS	$F(1,41)=3.2, p<.10$	$F(1,41)=11.3, p<.01$
Memory Span	$F(1,41)=0.5$, NS	$F(1,41)=3.8, p<.10$	$F(1,41)=0.1$, NS
Word Flash	$F(1,35)=6.8, p<.05$	$F(1,35)=8.0, p<.01$	$F(1,35)=1.4$, NS
Visual Search	$F(1,34)=0.3$, NS	$F(1,34)=5.9, p<.01$	$F(1,34)=0.1$, NS
Picture Naming	$F(1,38)=4.6, p<.05$	$F(1,38)=12.1, p<.001$	$F(1,38)=0.0$, NS
Color Naming	$F(1,38)=0.4$, NS	$F(1,38)=12.6, p<.001$	$F(1,38)=0.0$, NS
Digit naming	$F(1,38)=1.2$, NS	$F(1,38)=8.5, p<.01$	$F(1,38)=0.1$, NS
Letter Naming	$F(1,38)=2.3$, NS	$F(1,38)=8.4, p<.01$	$F(1,38)=0.2$, NS
Letter Naming %	$F(1,38)=3.7, p<.10$	$F(1,38)=0.3$, NS	$F(1,38)=0.3$, NS
Simple RT	$F(1,41)=22.2, p<.0001$	$F(1,41)=14.9, p<.001$	$F(1,41)=0.1$, NS
Selective CRT	$F(1,41)=0.2$, NS	$F(1,41)=8.6, p<.01$	$F(1,41)=0.1$, NS
Beads	$F(1,38)=11.0, p<.01$	$F(1,38)=1.8$, NS	$F(1,38)=0.1$, NS
Pegs	$F(1,38)=2.5$, NS	$F(1,38)=3.7, p<.10$	$F(1,38)=0.3$, NS
Balance 2 Feet	$F(1,40)=1.4$, NS	$F(1,40)=3.7, p<.10$	$F(1,40)=1.0$, NS
Balance 2 Feet Blindfold	$F(1,40)=2.0$, NS	$F(1,40)=2.6$, NS	$F(1,40)=0.2$, NS
Balance 1 Foot	$F(1,39)=2.8$, NS	$F(1,39)=17.7, p<.0001$	$F(1,39)=4.1, p<.05$
Balance 1 Foot Blindfold	$F(1,39)=21.6, p<.0001$	$F(1,39)=12.6, p<.001$	$F(1,39)=3.2$, NS
Balance Dual	$F(1,41)=7.8, p<.01$	$F(1,41)=1.0$, NS	$F(1,41)=7.4, p<.01$

Breadth of Deficit. Deficits were observed in all the primitive skills tested—phonological, speed, memory, and motor skill. There is no support here for any of the theories that attempt to tie dyslexia to one specific modality or type of process. In general the children with dyslexia were performing at or around the level of their reading age controls for speed of information processing and for memory, and below reading age for motor skill and phonological awareness.

Changes with Age. The most striking aspect of our data is the range of profound deficits suffered by the youngest children with dyslexia. If these cross-sectional data can be taken as a valid estimate of developmental change within individuals, it would seem that, following this very poor start, the children with dyslexia actually continue to make progress in speed of processing and in memory, possibly even catching up a bit. By contrast, there are persistent deficits in phonological skill and especially in balance as shown by the performance of the D16 group. This pattern of results suggests that the learning processes are essentially intact, but that skill acquisition is greatly hampered by the initial poor performance.

Specific Difficulties. While it is clear that there are problems in all primitive skills, it is also important to identify which types of skill show the greatest deficits, since this may give some clue as to the most likely cause(s). Among measures of print skills, the spelling and speeded word recognition tests led to a greater impairment than the reading test, for the two older ages. As noted above, phonological skill and motor skill appear to be least susceptible to developmental improvement, with information processing speed and memory showing the greatest improvement. It is also important to consider, within each modality, which type of skill was most affected. Consider first speed of reaction. Here we found that simple reactions were essentially normal, but that problems arose as soon as a decision was required (selective choice reaction). The choice reaction deficit occurred whether or not linguistic stimuli were involved, and regardless of whether the stimuli were visual or auditory. The group differences were roughly in line with reading age, and improvement with age roughly paralleled improvement in reading. Now consider motor skill. There were severe initial deficits in bead threading, pegboard manipulation, and normal balance but the latter two did at least improve with age. By contrast, the deficit in blindfold balance persisted into the oldest group, with performance worse than that of the C8 group. In phonological and memory tasks different patterns of results were obtained for different measures. There were weak or transient deficits for nonword repetition and speech rate; small but persistent impairments for phonological discrimination and memory span; and a marked and persistent impairment in rhyme and segmentation.

Overall Discussion

Our initial motivation was to explore the pattern of performance across the skill spectrum in the belief that it might be premature to opt for one or another hypothesis in the absence of this information. It seems clear from the results that our caution in advocating the collection of wide-ranging data before committing oneself to one or other theory was justified. It is not possible to account for the range of deficits shown merely in terms of one of phonological deficit, visual deficit, speed deficit, etc. The true cause or causes must surely lie deeper within the cognitive system.

It is also important to stress that, although we have found deficits in a range of primitive skills, this should not be taken to indicate any lack of mental ability. Far from it. We believe that the cognitive system (including intelligence and learning) is functioning at normal or above normal levels, as witnessed by the high achievements of many adults with dyslexia (West 1991). Adults with dyslexia are fortunate in having the ability to "consciously compensate" for these underlying difficulties in primitive skill, to the extent that these difficulties are apparently overcome in normal life.

It remains to consider the theoretical interpretation of the results. First let us consider our initial question "They can't all be right, can they!?" In one sense they all are. There are indeed phonological deficits, visual deficits, motor skill deficits, and speed deficits. Furthermore, the overall performance is well-described as showing an automatization deficit. But in this case, being right is not enough. Each of these theoretical positions has significant limitations in its ability to account for the whole range of results.

In order to characterize the results, we refer to performance significantly below that of reading age controls as a "severe deficit"; performance at around the level of reading level controls as a "moderate deficit"; and performance at or near the level of chronological controls as "normal." Severe deficits were therefore found for segmentation, rhyme, word flash, picture naming, bead threading, balance on 1 foot with blindfold, and balance dual. Normal performance was found for simple reaction, and moderate deficits were found for all the other tasks. Next we postulate that each theory will predict the following types of deficit: a severe deficit in those skills directly reliant on the proposedly faulty mechanism; a moderate impairment for skills in which the faulty mechanism is involved, but not centrally; and normal performance for skills in which the faulty mechanism is not involved.

Consider, first, the phonological deficit hypothesis. This predicts (correctly) severe deficits in rhyme/segmentation, moderate deficits in most of the other tasks, but no deficit for non-verbal skills such as simple reaction, selective choice reaction, and motor skill. The severe deficits in bead threading and balance are also quite contrary to its predictions of normal performance on that type of task.

A rapid processing deficit hypothesis (construed to include deficits in both visual and auditory processing) correctly predicts severe deficits in word flash and the various naming and choice reaction tasks, but it incorrectly predicts normal spelling, articulation speed, motor skill, and balance. Furthermore, the normal simple reaction performance appears inexplicable under this hypothesis.

Finally, the automatization deficit hypothesis predicts severe deficits for spelling (in that the faulty spelling skill acquisition overlays the faulty phonological processing skill), in word flash (since rapid word identification depends critically on automatization), and on dual task or blindfold balance (since the subject is prevented from consciously compensating for the underlying deficit). Overall, the automatization deficit hypothesis produces the best fit to the pattern of results obtained. While the fit of its predictions to the results is not perfect, each of its strong predictions has been confirmed, and this suggests that children with dyslexia may be well-characterized by our suggestion that they show a lack of automatization of skill. The hypothesis provides a remarkably parsimonious account of the data, accounting for difficulties in phonological skill, visual skill, motor skill, information processing speed, and, of course, reading. Furthermore, in many circumstances children and adults with dyslexia are able to compensate for this underlying lack of fluency by concentrating harder or using strategies (our conscious compensation hypothesis), thereby resulting in the characteristic signs of rapid tiring and distractibility.

However, an automatization deficit is itself merely a description. It does not explain, *inter alia*, the pattern of deficits—why simple reactions appear to be of normal speed, whereas choice reactions start slow but then improve at a normal rate; or why phonological skills are so poor. Most important, it does not explain why difficulties in most skills are most marked immediately, but then tend to diminish with practice. An explanation must surely appeal to deeper levels within the brain. Our results therefore raise as many questions as they resolve.

In conclusion, it seems that the single-mechanism explanations of dyslexia, which rely on a deficit in phonological, visual, motor, or temporal processing skill, are overly restrictive. There are deficits in *all* these facets of skill. The best general account of the range of performance deficits found in this study is given by our automatization deficit hypothesis, but that is probably best seen as an initial attempt to link dyslexia with general theories of skill acquisition rather than as a causal theory. A causal theory should surely attempt to link the range of deficits to underlying neural mechanisms. Rather than an awkward embarrassment, we believe that the range of deficits obtained in this study not only integrates what were previously rather disparate approaches, but also points the way to an exciting research program that explores the link between the brain and the mind.

References

Adams, M. J. 1990. *Beginning to Read: Thinking and Learning about Print.* Cambridge, MA: MIT Press.

Anderson, J. R. 1982. Acquisition of cognitive skill. *Psychological Review* 89:369–406.

Augur, J. 1985. Guidelines for teachers, parents and learners. *In* M. Snowling (ed.). *Children's Written Language Difficulties.* Windsor: NFER Nelson.

Baddeley, A. D., Thomson, N., and Buchanan, M. 1975. Word length and the structure of short term memory. *Journal of Verbal Learning and Verbal Behavior* 14:575–89.

Bishop, D. 1985. Spelling ability in congenital dysarthria: Evidence against articulatory coding in translating between graphemes and phonemes. *Cognitive Neuropsychology* 2:229–51.

Bradley, L., and Bryant, P. E. 1983. Categorising sounds and learning to read: A causal connection. *Nature* 301:419–21.

Denckla, M. B., and Rudel, R. G. 1976. Rapid 'Automatized' Naming (R.A.N.). Dyslexia differentiated from other learning disabilities. *Neuropsychologia* 14:471–9.

Duffy, F. H., Denckla, M. B., Bartels, P. H., and Sandini, G. 1980. Dyslexia: Regional differences in brain electrical activity by topographic mapping. *Annals of Neurology* 7:412–20.

Fawcett, A. J., and Nicolson, R. I. 1994a. Motor skill and dyslexia. *Journal of Motor Behavior,* in press.

Fawcett, A. J., and Nicolson, R. I. 1994b. Phonological skill and dyslexia. Submitted.

Fawcett, A. J., and Nicolson, R. I. 1994c. Naming speed and dyslexia. *Journal of Learning Disabilities,* in press.

Fawcett, A. J., and Nicolson, R. I. 1992. Automatisation deficits in balance for dyslexic children. *Peceptual and Motor Skills* 75:507–29.

Fitts P. M., and Posner, M. I. 1967. *Human Performance.* Belmont, CA: Brooks Cole.

Frith, U. 1985. Beneath the surface of developmental dyslexia. *In* K. E. Patterson, J. C. Marshall, and M. Coltheart (eds.). *Surface Dyslexia.* London: Lawrence Erlbaum Associates.

Galaburda, A. M., Rosen, G. D., and Sherman, G. F. 1989. The neural origin of developmental dyslexia: Implications for medicine, neurology and cognition. *In* A.M. Galaburda (ed.). *From Reading to Neurons.* Cambridge, MA: MIT Press.

Gathercole, S. E., and Baddeley, A. D. 1990. Phonological memory deficits in language disordered children: Is there a causal connection? *Journal of Memory and Language* 29:336–60.

Haslum, M. N. 1989. Predictors of dyslexia. *Irish Journal of Psychology* 10:622–30.
Hynd, G. W., Semrud, M., Lorys, A. R., and Novey, E. S. 1990. Brain morphology in developmental dyslexia and attention deficit disorder/hyperactivity. *Archives of Neurology* 47:919–26.
Leonard, C. M., Voeller, K. K. S., Lombardino, L. J., Morris, M. K., Hynd, G. W., Alexander, A. W., Andersen, H. G., Garofalkis, M., Honeyman, J. C., Mao, J., Agee, O. F., and Staab, E. V. 1993. Anomalous cerebral structure in dyslexia revealed with magnetic resonance imaging. *Archives of Neurology* 50:461–69.
Livingstone, M. S., Rosen, G. D., Drislane, F. W., and Galaburda, A. M. 1991. Physiological and anatomical evidence for a magnocellular deficit in developmental dyslexia. *Proceedings of the National Academy of Sciences of the USA* 88:7943–47.
Lovegrove, W. J., Garzia, R. P., and Nicholson, S. B. 1990. Experimental evidence of a transient system deficit in specific reading disability. *Journal of the American Optometric Association* 61:137–46.
Lubs, H. A., Duara, R., Levin, B., Jallad, B., Lubs, M., Rabin, M., Kusch, A., and Gross-Glenn, K. 1991. Dyslexia subtypes: Genetics, Behaviour and Brain Imaging. *In* D. D. Duane and D. B. Gray (eds.). *The Reading Brain: The Biological Basis of Dyslexia.* Parkton, MD: York Press.
Miles, T. R. 1993. *Dyslexia: The Pattern of Difficulties.* 2nd Edition. London: Whurr.
Miles, T. R. 1983. *Dyslexia: The Pattern of Difficulties.* London: Granada.
Newell, A. 1973. You can't play 20 questions with Nature and win: Comments on a symposium. *In* W. Chase (ed.). *Visual Information Processing.* London: Academic Press.
Nicolson, R. I. 1993. The Cognitive Operations Multimedia Battery. *Internal report LRG 93/14.* University of Sheffield.
Nicolson, R. I., and Fawcett, A. J. 1994. Reaction times and dyslexia. *Quarterly Journal of Experimental Psychology.* 47A:29–48.
Nicolson, R. I., and Fawcett, A. J. 1992. Toward the origins of dyslexia. *In* J. K. Kruschke (ed.). *Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society.* Hillsdale, NJ: Lawrence Erlbaum Associates.
Nicolson, R. I., and Fawcett, A. J. 1990. Automaticity: A new framework for dyslexia research? *Cognition* 30:159–82.
Rosner, J., and Simon, D. P. 1971. The auditory analysis test: An initial report. *Journal of Learning Disabilities* 4:384–92.
Rudel, R. G. 1985. The definition of dyslexia: Language and motor deficits. *In* F. H. Duffy and N. Geschwind (eds.). *Dyslexia: A Neuroscientific Approach to Clinical Evaluation.* Boston: Little Brown.
Shiffrin, R. M., and Schneider, W. 1977. Controlled and automatic human information processing: II. Perceptual learning, automatic attending and general theory. *Psychological Review* 84:127–90.
Smith, S. D., Kimberling, W. J., Pennington, B. F., and Lubs, A. A. 1983. Specific reading disability: Identification of an inherited form through linkage analysis. *Science* 219:1345–7.
Snowling, M. J., Goulandris, N., Bowlby, M., and Howell, P. 1986. Segmentation and speech perception in relation to reading skill: A developmental analysis. *Journal of Experimental Child Psychology* 41:487–507.
Stanovich, K. E. 1988. The right and wrong places to look for the cognitive locus of reading disability. *Annals of Dyslexia* 38:154–77.
Stein, J. F. 1989. Visuospatial perception and reading problems. *Irish Journal of Psychology* 10:521–33.
Tallal, P. 1984. Temporal or phonetic processing deficit in dyslexia? That is the question. *Applied Psycholinguistics* 5:167–9.
Thomson, M. E. 1984. *Developmental Dyslexia: Its Nature, Assessment and Remediation.* London: Edward Arnold.

Vellutino, F. R. 1979. *Dyslexia: Theory and Research.* Cambridge, MA. MIT Press.
Wechsler, D. 1976. *Wechsler Intelligence Scale for Children-Revised* (WISC-R). Slough, NFER.
West, T. G. 1991. *In the Mind's Eye.* New York: Prometheus.
Wolf, M. 1991. Naming speed and reading: The contribution of the cognitive neurosciences. *Reading Research Quarterly* 26:123–41.
Wolff, P. H., Michel, G. F., and Ovrut, M. 1990. Rate and timing precision of motor coordination in developmental dyslexia. *Developmental Psychology* 26:349–59.