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A double dissociation between sensorimotor impairments and reading disability: A comparison of autistic and dyslexic children

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Does sensorimotor dysfunction underlie reading impairment? To investigate this question, a battery of literacy, phonology, auditory, visual, and motor tests were administered to age- and ability-matched groups of dyslexic, autistic, and control children. As in previous studies, only a subset of the dyslexic children had sensory and/or motor impairments, whilst some dyslexics were entirely spared, suggesting that sensorimotor impairments are not necessary to cause reading disability. A subset of autistic children was also found to have sensorimotor impairments; however, some of these children did not have reading problems, suggesting that sensorimotor impairments are not sufficient to cause reading disability. We conclude that sensorimotor and reading impairments are doubly dissociable. Sensorimotor impairments do not seem to be the cause of reading disability, but can be seen as nonspecific markers for developmental disorder.

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Developmental disorders are complex and often appear to be very heterogeneous; it is therefore difficult to identify the causes of the main symptoms. Indeed, the aetiology of developmental dyslexia is currently the subject of a debate between two main opposing views. One view proposes that reading disability is due to a cognitive impairment specific to phonological processing (Snowling, 2000; Vellutino, 1979), arising from a dysfunction of certain left-hemisphere peri-sylvian brain areas (McCandliss & Noble, 2003; Paulesu et al., 2001; Shaywitz et al., 1998). The other view recognizes the role played by the phonological deficit but sees it as only one consequence of a more general sensorimotor syndrome, including auditory, visual, and motor dysfunctions. If so, the biological origin of this syndrome might be a pan-sensory magnocellular dysfunction with secondary disruption to the cerebellum and hence motor systems (Stein, 2001; Stein & Walsh, 1997), or a general learning disability based on cerebellar dysfunction (Nicolson, Fawcett, & Dean, 2001). Recently, this view has been challenged by evidence suggesting that sensorimotor dysfunction affects only a fraction of dyslexics, questioning its causal contribution to reading failure (see Ramus, 2003, for a recent review).

Nevertheless, although sensorimotor impairments may not be necessary to cause reading disability, they may be sufficient; they might provide a valid explanation of reading disability for the subset of affected dyslexics. This would predict that reading disability would occur whenever an individual was affected by such sensorimotor impairments. This prediction is particularly interesting since the sensorimotor impairments documented in dyslexia are not restricted to the dyslexic population. Visual magnocellular deficits have been found in autism (Gepner & Mestre, 2002; Milne et al., 2002; Spencer et al., 2000) and Williams syndrome (Atkinson et al., 1997), auditory deficits have been found in specific language impairment (SLI; Tallal & Piercy, 1973; Wright et al., 1997) and autism (Oram Cardy, Flagg, Roberts, Brian, & Roberts, 2005), and motor deficits have been found in autism (Courchesne, 1997; Hallett et al., 1993; Noterdaeme, Mildenberger, Minow, & Amorosa, 2002), Williams syndrome (Jones et al., 2002), SLI (Hill, 2001), and of course developmental coordination disorder (DCD; Hill, 1998).

Sensorimotor impairments therefore seem to be more generally found in a large variety of developmental disorders, in which reading disability is not necessarily a characteristic feature. However, assessments of the reading abilities of such populations are not routinely performed. In the case of autism, reading ability varies widely from none to hyperlexic (Whitehouse & Harris, 1984) and therefore presents a suitable testing ground for the hypothesis that sensorimotor impairments have the same putative effects on reading outside the "official" dyslexic population. The present study therefore compares literacy, phonology, auditory, visual, and motor skills between dyslexic and autistic children, with the aim of evaluating the relationship between sensorimotor dysfunction and reading disability.

Method

The present study reports novel analyses of data that have been partially published before. More specifically, the data obtained on dyslexic and control children were reported by White et al. (2006), while the visual and motor data obtained on autistic children were reported by Milne et al. (in press). Literacy, phonology, and auditory data from the autistic children have not been reported before. The originality of the present paper is in the comparison between the dyslexic and autistic populations across the whole range of abilities.

Participants

In total, 22 autistic children were compared to 23 dyslexic and 22 control children. The groups were chosen to be matched on their range of ages and nonverbal IQs: age, $F(2, 64) = 1.02$; nonverbal IQ, $F(2, 64) = 1.93$. All children were aged between 8 and 12 years and had nonverbal IQs of at least 85, with the exception of 4 high-functioning and able autistic children with nonverbal IQs of 70, 73, 79, and 84, as measured by

Raven's Standard Progressive Matrices (Raven, Court, & Raven, 1988); raw scores were converted to standardized scores by interpolation and extrapolation from percentile scores given in the manual. The autistic children had all independently received a diagnosis of autism, autistic spectrum disorder, or Asperger syndrome and were recruited through special schools for children with such diagnoses. The majority of the dyslexic children were referred from the Dyslexia Institute and had therefore received the same neuropsychological assessment from the same highly experienced educational psychologist. All participants had pure-tone detection thresholds below 25 dB in both ears across a range of frequencies (0.5–8 Hz).

Procedure

The study obtained ethical approval from the Joint UCL/UCLH Committees on the Ethics of Human Research, and informed consent to participate was given by both parent and child. Children were tested individually in a quiet room at their home, at their school, or at the Institute of Cognitive Neuroscience. Testing was divided into three sessions of approximately an hour each, and every child completed a battery of tasks assessing literacy, phonology, auditory, visual, and motor abilities. The sensorimotor tests were chosen to reflect those currently in use by the proponents of each theory and on which they have found significant group differences. Further methodological details can be found in White et al. (2006).

Literacy tests

The children were tested on the Wide Range Achievement Test (WRAT3; Wilkinson, 1993), a standardized literacy assessment, to provide a measure of their single-word reading and spelling skills.

Phonology tests

The Phonological Assessment Battery (PhAB; Frederickson, Frith, & Reason, 1997), another standardized assessment, was used to assess skill at processing and manipulating speech sounds. The rhyme, spoonerisms, nonword reading, rapid automatic naming (two tests), and fluency (three tests) subtests were all administered according to the test manual. It should be noted that one of the fluency tasks (semantic fluency) is a non-phonological control task.

Auditory tests

All auditory tasks were run on a laptop computer using calibrated headphones. Two tasks involving the categorization of phonemes were presented, using single stimuli from the speech sound continua /ba/–/da/ and *coat–goat*. A further task using the /ba/–/da/ continuum involved the discrimination of a pair of identical sounds from a pair of differing sounds, and a nonspeech version of this task was also administered, using only the second formant (tasks as in Ramus et al., 2003, and Rosen & Manganari, 2001). Finally, the children were required to detect which of two tones was frequency modulated (FM) at 2 Hz (task inspired from Witton et al., 1998). Each task was performed twice, and the best performance was recorded.[1]

Visual tests

Both the motion coherence and form coherence tasks were run on a laptop computer (tasks as in Hansen et al., 2001). In both tasks, participants viewed two panels on the screen and judged which contained the coherent signal. In the critical condition, dots moving coherently from side to side were presented in one panel, and in the control condition, a coherent circular form made up of line elements was presented in one panel. The second panel always contained a random

[1] Reliability analysis indicated that performance between the two trials of each task was inconsistent, more so for some tasks than others (Cronbach's alpha: /ba/–/da/ = .24, *coat–goat* = .33, FM 2 Hz = .65, speech formant discrimination = .35, nonspeech formant discrimination = .56). Such inconsistency may indicate additional task demands required to perform these tasks well; indeed, we believe that these tasks have a particularly high attentional load. We therefore took the best performance on a particular task as the most reliable measure of a child's auditory abilities, independent of other task demands.

signal: dots moving in random directions or line elements in random orientations. A weighted adaptive staircase procedure was used to present different levels of coherence in the signal, from which a detection threshold was calculated. Catch trials were also included to check that the children understood the task and were attending to its demands. Each condition was performed twice, and the average detection threshold was calculated.[2]

Motor tests

Motor skill was assessed using two manual dexterity and two balance tasks. As measures of manual dexterity, the child was required to thread beads onto a string (Fawcett & Nicolson, 1996) and also to perform a task known as finger and thumb (Dow & Moruzzi, 1958), involving rotation of the hands with thumb and index finger of opposite hands touching. Both balance tasks were taken from the Movement Assessment Battery for Children (Henderson & Sugden, 1992): a one-legged balance task (stork balance) and heel-to-toe (walking along a line with heel and toe touching). All tasks were performed twice, and average performance was recorded.[3]

Results

ANOVAs were used to assess differences between groups, unless otherwise stated; due to multiple comparisons, we chose to set our alpha level to $p = .01$. As well as group differences, individual differences in performance were studied, and outliers with abnormally low performance were identified as lying more than 1.65 standard deviations (*SD*s) below the control mean, equivalent to the bottom 5% of a normal distribution (procedure as in Ramus et al., 2003). Summary factors, accounting for all tasks in a given modality, were also calculated by averaging z-scores (calculated in relation to control performance) for each participant across tasks in each modality.

Literacy tests

As expected, the groups differed on reading, $F(2, 64) = 28.60$, $p < .001$, and spelling tasks, $F(2, 64) = 28.51$, $p < .001$. However, pairwise comparisons revealed not only that the dyslexic group performed worse than the control group on both tasks ($p < .001$) but that the autistic group also did ($p < .001$). A very marginal difference existed between the dyslexic and autistic groups (read $p = .092$; spell $p = .064$), indicating that, as a group, the autistic children were not quite as impaired as the dyslexics on the reading and spelling tasks. The nonword reading test revealed the same pattern of differences between groups, $F(2, 64) = 20.88$, $p < .001$, with both dyslexic ($p < .001$) and autistic children ($p = .003$) performing more poorly than controls, and dyslexic children performing slightly more poorly than autistic children ($p = .013$). (See Table 1.)

A literacy factor was calculated by combining reading, spelling, and nonword reading scores. A total of 96% of dyslexic children were outliers on this factor, while 59% of autistic children and 18% of controls were. This factor was found to be weakly correlated to nonverbal IQ in the whole sample ($r = .26$, $p = .037$) and more strongly in the control and dyslexic groups (control, $r = .57$, $p = .006$; dyslexic, $r = .55$, $p = .006$) but not in the autistic group ($r = .06$). Given the overall IQ–literacy correlation, individual differences in nonverbal IQ were taken into account by entering each summary factor as the dependent variable in a regression analysis with nonverbal IQ as the independent variable. Unstandardized residuals for each participant were recorded from this analysis as the corrected

[2] Reliability analysis indicated that performance between the two trials of each task was consistent; Cronbach's alpha: motion (ranked data as not normally distributed) = .74, form = .6. We therefore took the average performance to be the most reliable measure of a child's abilities.

[3] Reliability analysis indicated that performance between the two trials of each task was highly consistent; Cronbach's alpha: bead threading (ranked data) = .84, finger and thumb = .87, heel-to-toe (ranked data) = .88, stork balance (ranked data) = .84. We therefore took the average performance to be the most reliable measure of a child's abilities.

Table 1. *Background and literacy test means*

	Control	Dyslexic	Autistic All	Autistic Good reader	Autistic Poor reader
Number	22	23	22		
Male:female	9:13	14:9	20:2		
Age[a]	123.82 (13.73)	126.04 (15.01)	119.27 (19.36)		
Nonverbal IQ	102.95 (13.88)	102.13 (13.21)	95.59 (13.83)		
Reading***	112.64 (10.57)	85.78*** (11.86)	93.55*** (13.98)		
Spelling***	113.23 (12.94)	84.83*** (9.27)	93.64*** (15.74)		
Nonword reading***	114.95 (12.68)	93.39*** (6.74)	103.18** (13.18)		
Original literacy factor***	0.00 (1.00)	− 2.42*** (0.78)	− 1.60*** (1.22)		
Corrected literacy factor***	0.00 (1.00)	− 2.83*** (0.77)		− 0.20 (0.89)	− 2.67*** (0.92)

Note: Test scores are standardized scores. Literacy factor scores are based on averaged z-scores. Stars next to the test name indicate an overall group difference. Stars within the table indicate differences between that group and the control group. Standard deviations in parentheses.

[a]In months.

$^{**}p < .01$; $^{***}p < .001$.

summary factor. The literacy factor was therefore recalculated, group difference, $F(2, 64) = 25.02$, $p < .001$, and all 23 dyslexics were found to be outliers. The literacy scores of the autistic children were extremely wide ranging and were therefore divided into two groups of good and poor readers, resulting in 9 children falling above (good readers) and 13 children falling below (poor readers) the outlier threshold. This division does not make the assumption that the autistic poor readers were dyslexic (as they may have other reasons to read poorly); rather it rules out the possibility that any of the autistic good readers had a reading disability. These two groups of autistic children were entered separately into all further analyses. Two controls were also literacy outliers and were therefore removed from all further analysis as it could not be assumed that their literacy development was normal.

Phonology

Group differences were found on all of the PhAB subtests ($F > 4$, $p \leq .008$) except alliteration fluency, $F(3, 61) = 0.302$, $p = .824$, on which the control group performed worse than expected, given the scores on the other subtests. Pairwise comparisons revealed that the dyslexics had severe phonological problems, performing worse than controls on all the phonological subtests ($p \leq .001$, except rhyme fluency where $p = .028$). Similarly, the autistic poor readers performed worse than controls on these same tasks ($p \leq .002$) except for rapid automatic picture naming ($p = .238$). However, unlike the dyslexics, both autistic groups also performed marginally worse than controls on the nonphonological semantic fluency task (poor readers, $p = .025$; good readers, $p = .023$) despite the autistic good readers performing as well as the controls on all the phonological tasks. This is likely to be due to the presence of poor semantic skills in autism.

The scores from the six phonological tasks were combined to give a phonology factor, and after accounting for nonverbal IQ, 48% of the dyslexic children, 38% of the autistic poor readers, and 33% of the autistic good readers[4] were found to be outliers (no control outliers), $F(3, 61) = 10.121$, $p < .001$ (see Table 2).

[4] It should be noted that the phonological measures used here may tap other abilities, particularly general processing speed in the rapid automated naming tests. We include these tests as they have been shown to be sensitive to the phonological impairment in dyslexia (see Frederickson et al., 1997). However, it is possible that some autistic children may therefore be defined as phonological outliers for nonphonological reasons.

Table 2. *Phonology test means*

			Autistic	
	Control	*Dyslexic*	*Good reader*	*Poor reader*
Rhyme***	112.30 (11.89)	96.26** (14.09)	98.33 (15.54)	89.77*** (13.38)
Spoonerisms***	112.80 (11.08)	98.00*** (9.19)	110.56 (3.00)	97.00*** (14.46)
Rapid automatic picture naming**	108.75 (12.93)	92.22** (12.76)	100.44 (16.69)	99.25 (14.28)
Rapid automatic digit naming***	109.25 (12.51)	88.83*** (9.67)	101.00 (18.5)	91.00** (17.26)
Alliteration fluency	100.05 (7.98)	99.61 (10.66)	100.00 (14.11)	96.62 (13.44)
Rhyme fluency**	114.55 (10.82)	101.70* (11.93)	103.33 (14.47)	92.85*** (18.58)
Semantic fluency**	107.10 (11.06)	100.65 (15.29)	90.00* (13.92)	92.08* (17.68)
Phonology factor***	0.00 (1.00)	− 1.62*** (0.96)	− 0.69 (1.50)	− 1.89*** (1.47)

Note: Test scores are standardized scores. Phonology factor scores are based on averaged z-scores. Stars next to the test name indicate an overall group difference. Stars within the table indicate differences between that group and the control group. Standard deviations in parentheses.
$^{**}p < .01$; $^{***}p < .001$.

Auditory tasks

The full auditory data from one autistic child was lost, whilst 3 dyslexics and 4 controls were without data for the /ba/−/da/ and *coat*−*goat* tasks due to the use of incorrect task parameters. The only task to produce a significant group difference was the FM at 2 Hz task, $F(3, 60) = 7.19$, $p < .001$, and this was due to both autistic groups performing more poorly than controls (poor readers, $p = .014$; good readers, $p = .001$) and the good readers performing worse than the dyslexics ($p = .007$; see Table 3). Individual performance on all tasks appeared to follow little pattern, with different children having difficulties on different tasks. On combining the results from the five experimental tasks into an auditory factor and accounting for age as well as nonverbal IQ (as none of the sensorimotor tasks was standardized for age, unlike the literacy and phonological tasks), a marginal group difference was found, $F(3, 60) = 2.928$, $p = .041$, with the autistic poor readers performing slightly worse than controls ($p = .055$). A total of 30% of dyslexics, 38% of autistic poor readers, and 50% of autistic good readers were found to be outliers (10% control outliers).

Table 3. *Auditory test means*

			Autistic	
	Control	*Dyslexic*	*Good reader*	*Poor reader*
/ba/−/da/	3.49 (4.38)	3.99 (4.73)	4.16 (3.77)	3.21 (3.98)
coat−*goat*	2.99 (1.13)	5.05 (5.31)	7.08 (7.76)	8.38 (7.30)
FM 2 Hz***	1.98 (2.15)	2.64 (2.44)	6.53** (3.71)	5.11* (3.62)
Formant (speech) discrimination	6.63 (3.31)	6.27 (4.88)	9.23 (6.05)	8.31 (5.41)
Formant (nonspeech) discrimination	6.33 (3.83)	6.05 (4.03)	7.00 (4.76)	7.56 (4.85)
Auditory factor*	0.00 (1.00)	−0.52 (1.74)	−1.60 (2.61)	−1.71 (2.44)

Note: Test scores are quoted as just-noticeable-differences/modulation indexes for FM tasks (low scores indicate good performance). Auditory factor scores are based on averaged z-scores. Stars next to the test name indicate an overall group difference. Stars within the table indicate differences between that group and the control group. Standard deviations in parentheses.
$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

Visual tasks

A minority of children failed more than one catch trial across both measurements for each condition. Subsequently, the data for any child who failed more than 20% of catch trials on a measurement were removed from the analysis. This meant that 5 autistic children on the motion coherence task and 1 autistic child on the form coherence task had a test score based on one rather than two measurements. One further autistic child had extremely poor catch trial performance on the motion coherence task, failing 38% and 43% of catch trials on the two measurements, as well as poor motion coherence thresholds, and appeared to find the task extremely difficult. However, his good catch trial performance on the form coherence task as well as his general high levels of motivation during testing indicated that he had a specific problem with motion coherence rather than a general attention problem. His results were therefore not excluded. In addition, the motion coherence task data were lost for one dyslexic child due to technical problems.

The motion coherence task produced a borderline significant difference between the groups, $F(3, 60) = 2.570$, $p = .063$, whereas the control form coherence task did not, $F(3, 61) = 2.116$; see Table 4). Pairwise comparisons revealed no significant group differences on either task. After accounting for both nonverbal IQ and age, 13% of dyslexics, 31% of autistic poor readers, and 33% of autistic good readers were outliers on the motion task (10% control outliers) while 17% of dyslexics, 23% of autistic poor readers, and 22% of autistic good readers were outliers on the form task (5% control outliers). However, 3 autistic children (1 good reader and 2 poor readers) had poor performance far out of the range of either the dyslexics or controls on the motion task. These children appeared to have such severe problems with motion detection that they could hardly perform the task at all, whilst only one of these children also had problems with form coherence detection.

The two visual tasks were not combined to create a single visual factor as they are believed to tap different aspects of visual processing.

Table 4. *Visual test means*

			Autistic	
	Control	*Dyslexic*	*Good reader*	*Poor reader*
Motion	10.17 (4.28)	10.53 (3.30)	18.78 (15.66)	15.91 (16.13)
Form	27.08 (4.10)	27.58 (7.43)	29.52 (3.10)	32.39 (9.90)

Note: All comparisons are nonsignificant. Test scores are coherence thresholds (low scores indicate good performance). Standard deviations in parentheses.

Motor tasks

The data from all the motor tasks were found to have distributions significantly different from the normal distribution (Shapiro–Wilk's test) so nonparametric analysis was required (Kruskal–Wallis H-test, approximated to the χ^2 distribution). Group differences were found on all four motor tests, although the balance tasks were more marginal than the manual dexterity tasks (bead threading, $\chi^2 = 12.711$, $p = .005$; finger & thumb, $\chi^2 = 17.075$, $p = .001$; heel-to-toe, $\chi^2 = 9.777$, $p = .021$; stork balance, $\chi^2 = 10.295$, $p = .016$). The dyslexics were marginally worse than controls only at the stork balance task ($p = .030$) while the autistic poor readers were marginally worse at both balance tasks (heel-to-toe, $p = .054$; stork balance, $p = .024$), and the autistic good readers were marginally worse at the finger and thumb and the heel-to-toe task (finger and thumb, $p = .012$; heel-to-toe, $p = .012$; see Table 5). A motor variable, accounting for both nonverbal IQ and age, was produced by combining scores over all these tasks, and a group difference was found on this factor, $F(3, 63) = 6.43$, $p = .001$, with both autistic groups performing worse than controls (good readers, $p < .001$, poor readers, $p = .005$). A total of 17% of dyslexics, 38% of autistic poor readers, and 56% of autistic good readers were found to be outliers (no control outliers). Again, a number of the autistic children had poor performance well outside the range of the dyslexics and controls.

Table 5. *Motor test means*

			Autistic	
	Control	*Dyslexic*	*Good reader*	*Poor reader*
Bead threading[a]**	55.53 (6.84)	54.50 (13.14)	78.84 (24.83)	61.85 (11.88)
Finger & thumb[a]**	8.70 (2.95)	8.33 (1.57)	26.20* (18.33)	19.98 (17.42)
Heel-to-toe[b]*	15.00 (0.00)	13.57 (3.60)	10.89* (5.16)	12.69 (4.52)
Stork balance[a,c]*	19.33 (2.28)	16.88* (5.20)	17.37 (5.80)	13.72* (6.58)
Motor factor**	0.00 (1.00)	−0.47 (1.60)	−3.47 (3.98)	−2.27 (3.46)

Note: Low scores in bead threading and finger and thumb indicate good performance; high scores in heel-to-toe and stork balance indicate good performance. Motor factor scores are based on averaged z-scores. Stars next to the test name indicate an overall group difference. Stars within the table indicate differences between that group and the control group. Standard deviations in parentheses.
[a]In s. [b]No. of steps, 15 max. [c]20 max.
*$p < .05$; **$p < .01$; ***$p < .001$.

Correlates of reading ability

In order to study the extent to which the different impairments are able to predict literacy ability, correlations between the corrected summary variables were performed. As the sensorimotor variables were not normally distributed, they were first rank ordered. As can be seen from Figure 1, phonology is a good predictor of literacy skill, as a strong correlation was found between the literacy and phonology factors in the whole sample ($r = .716$, $p < .001$), as well as within each of the groups (control, $r = .484$, $p = .031$; dyslexic, $r = .851$, $p = .004$; autistic poor readers, $r = .650$, $p = .016$; autistic good readers, $r = .670$, $p = .048$). Other marginal correlations were found in the whole sample between the phonology factor and visual motion ($r = .265$, $p = .034$) and motor ($r = .283$, $p = .022$) factors, as well as between the auditory, visual motion, and motor factors (auditory and visual, $r = .337$, $p = .007$; auditory and motor, $r = .461$, $p < .001$; visual and motor, $r = .379$, $p = .002$). However, these correlations only held within the control group. No other correlations were significant.

A multiple linear step-wise regression was performed to investigate which factors, from phonology, auditory, visual motion, and motor, could predict the variance in literacy performance (sensorimotor factors rank ordered). The phonology factor accounted for 52% of the variance in literacy performance, $F(1, 61) = 67.2$, $p < .001$, whilst none of the other factors was found to be a significant predictor of literacy. This was also found to be true when regressions were performed for each group separately. Literacy skill can therefore be explained in the majority of cases by phonological skill alone, after accounting for age and general ability.

Occurrence of impairments

Figure 2 shows all the children grouped by their deviant performance on different tasks. In total, 48% of dyslexics, 54% of autistic poor readers, and 67% of autistic good readers had one or more sensorimotor impairments, as did 15% of controls. Although the autistic good readers performed much better than the dyslexics on the literacy factor, $t(30) = 8.347$, $p < .001$, and marginally so on the phonology factor, $t(30) = 2.087$, $p = .045$, they did not differ on the auditory, $t(29) = 1.298$, and visual motion, $t(8.3) = 1.496$, factors and were marginally worse than the dyslexics on the motor factor, $t(9.0) = 2.197$, $p = .056$. Similarly, although autistic good readers performed better than autistic poor readers on the literacy factor, $t(20) = 6.288$, $p < .001$, and marginally better on the phonology factor, $t(20) = 1.860$, $p = .078$, they did not differ on any sensorimotor factor ($t < 0.8$). Furthermore, those dyslexics with sensorimotor impairments were no worse than those without

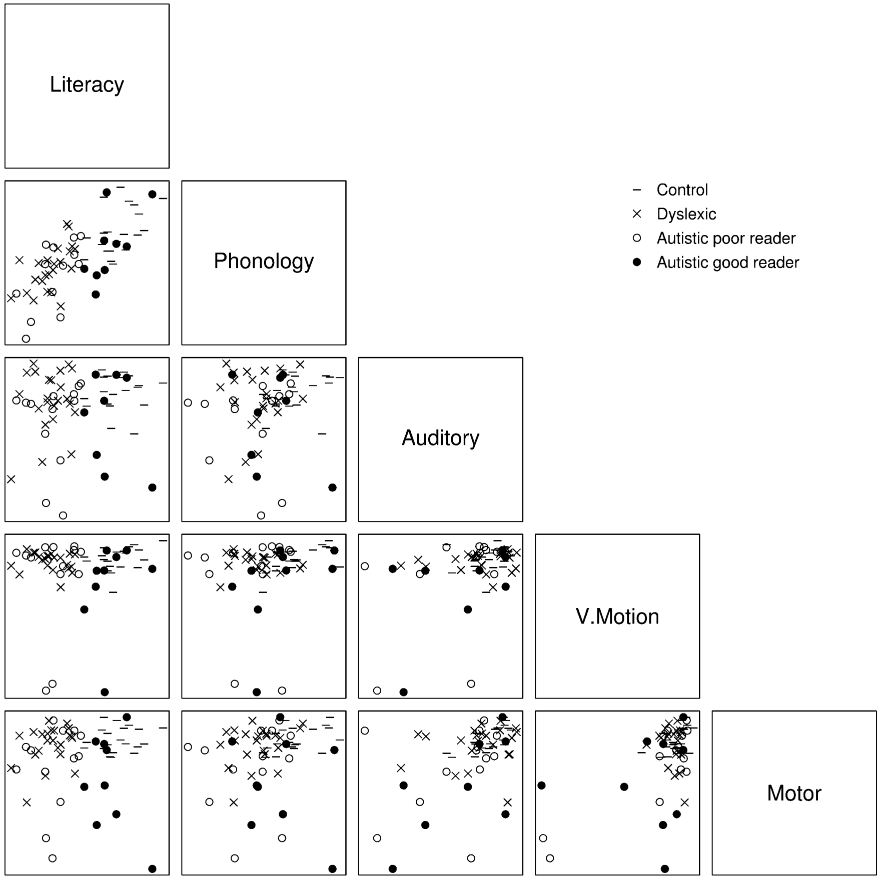

Figure 1. *Summary of correlations between literacy, phonology, auditory, visual motion, and motor factors. Good scores for each plot are in the top right corner, poor scores in the bottom left. The x-axis is denoted by the label above for each plot, the y-axis by the label to the right. The axes' scales are determined by the range of values present in the data set; the range within the control group should therefore be used as a basis for comparison to determine normal performance on each measure.*

on both phonology and literacy measures: literacy, $t(15.2) = 0.888$; phonology, $t(21) = 0.982$. Together, these comparisons suggest that differences in reading ability are not paralleled by differences in sensorimotor function.

Double dissociations

Figure 2 indicates not only that there is no relationship between sensorimotor and reading impairments, but also that there are complete double dissociations between the two domains. Indeed, it can be seen that 6 autistic children (as well as 3 controls) achieve normal reading skills despite one or several sensorimotor impairments.[5] Even with a full combination of visual, auditory, and motor impairments, 2 autistic children manage to read normally. This contrasts with 12 dyslexics who have a clear reading deficit without any evidence of sensorimotor impairment. For a more detailed illustration of

[5] Furthermore, of the 3 autistic and 2 control children who were outliers on the visual motion task but had good reading, only 1 of the autistic children was also an outlier on the control form task indicating that, for the majority, their sensorimotor impairments were specific rather than attributable to more general factors such as attention.

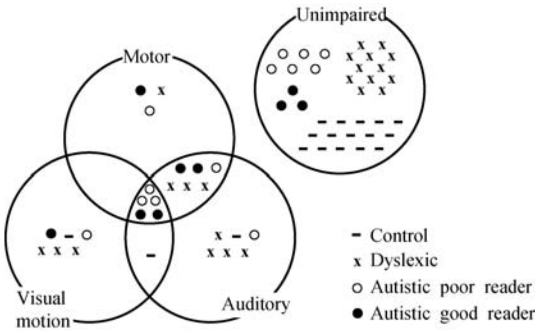

Figure 2. *Classification of all children by modality of impairment, when impairment is defined as more than 1.65 standard deviations below the control mean.*

these double dissociations, individual profiles of some of the most contrasted cases are provided in Figure 3.

The double dissociation logic can be criticized for setting arbitrary deviance thresholds and artificially splitting the subjects into impaired and intact categories, while there might be little difference between subjects whose scores are just above or below the thresholds. However, examination of Figure 3 shows that the present double dissociations are no artefact of deviance thresholds. Indeed, most subjects shown here have scores well beyond the thresholds chosen: Several severe dyslexics show average or superior performance in all sensorimotor domains (e.g., AF, RE, and TS), while several autistic good readers have extremely poor sensorimotor skills (indeed poorer than the poorest dyslexics; e.g., AR, IH, and JM). Furthermore the numbers involved here on each side of the dissociation (6 vs. 12) make it difficult to dismiss such cases as unrepresentative exceptions.

Discussion

Previous research has shown that dyslexics, as a group, present a variety of sensory and/or motor impairments (e.g., Nicolson et al., 2001; Stein & Walsh, 1997). Such evidence has been used to propose that the underlying cause of developmental dyslexia is to be found in general sensorimotor impairments (for instance, general magnocellular or cerebellar dysfunction) rather than in a specific phonological deficit. However, only a fraction of dyslexics seem to be affected by such sensorimotor impairments, as demonstrated by recent studies (Ramus et al., 2003; White et al., in press) and meta-analyses of the published literature (Ramus, 2003). It therefore seems that sensorimotor impairments can be the cause of reading disability in at best a subset of dyslexic children. But are they, really?

If they are, then one prediction is that all children who exhibit similar sensorimotor impairments should also be reading disabled. Building on previous research showing that at least a subset of autistic children has similar auditory, visual, and motor impairments, we have systematically investigated sensorimotor and reading impairments in matched groups of dyslexic, autistic, and control children.

We found that a subset of both dyslexic and autistic populations do indeed show sensorimotor impairments. Such impairments are rather more prevalent in the autistic than in the dyslexic population. However, sensorimotor impairments occurred in a pattern that was entirely independent of the occurrence of reading disability. Indeed, sensorimotor variables explained no variance in literacy. Neither dyslexics nor autistic poor readers showed more sensorimotor impairments than autistic good readers. Furthermore, many dyslexic and autistic children had neither sensory nor motor problems but still had poor literacy and phonology scores, indicating that sensorimotor deficits are not a necessary cause of reading impairment. Similarly, many autistic good readers had sensorimotor problems whilst displaying preserved literacy and phonological abilities, indicating that sensorimotor impairments are not sufficient to result in reading difficulties. These parallel findings of dyslexics without sensorimotor impairment, and autistic children without reading problems but with sensorimotor impairment, indicate that sensorimotor and reading impairments are doubly dissociable. Overall we find no relationship whatsoever between sensorimotor and reading impairments.

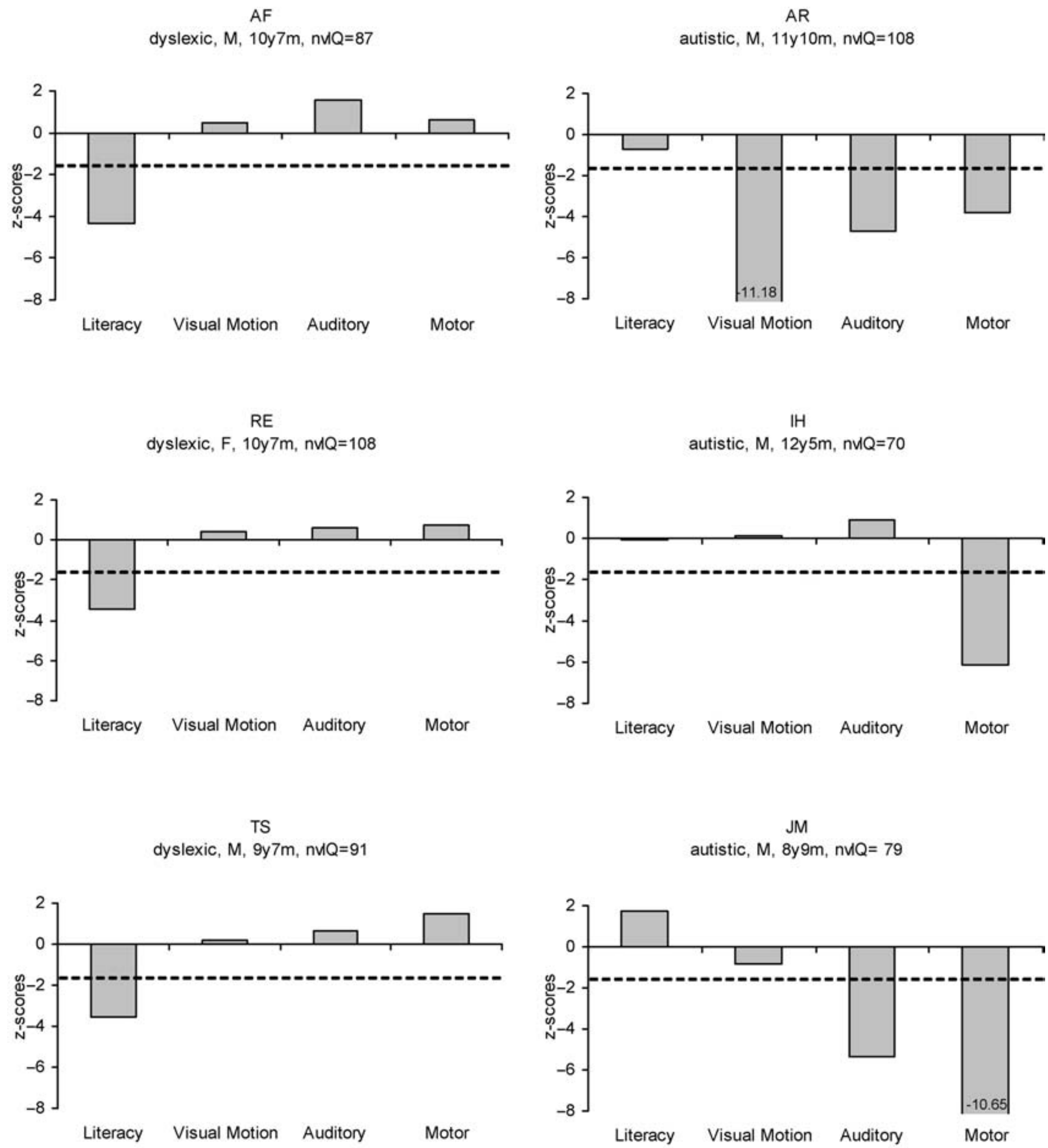

Figure 3. *Profiles for 6 participants illustrating the double dissociation between reading and sensorimotor impairments. The x-axis denotes z-scores based on the control group, and the dotted line indicates performance at 1.65 standard deviations below the control mean.*

While sensory and/or motor theories of dyslexia are sometimes presented as unifying theories explaining all cases (Stein & Walsh, 1997), more realistic versions of these theories acknowledge the possible existence of subtypes within the populations and claim to account for only some affected individuals (Tallal, 2004). In that case, our focusing on a few cases not affected by sensorimotor deficits might seem unfair and irrelevant to these theories. Yet even these weaker versions would predict that when a sensorimotor deficit of the specified type is present, it does cause a reading impairment. This prediction runs against our finding of cases with sensorimotor deficits but without reading impairment. That is, even accounting for different subtypes of dyslexia with different aetiology, the pattern of double dissociations that we have observed is generally inconsistent with sensorimotor theories.

Obviously, double dissociations should be interpreted more cautiously in developmental than in acquired disorders (Paterson, Brown, Gsödl, Johnson, & Karmiloff-Smith, 1999). The pattern of impairments may indeed change throughout development, so that the cross-sectional picture that we have taken here might not reflect the pattern of impairments at an earlier stage of development more relevant to language and reading acquisition. But what are the alternative interpretations of the present data? An interpretation consistent with a sensorimotor theory of dyslexia would need to assume: (a) that sensorimotor impairments are present in all dyslexics at birth, but recover in most of them before the time of testing; and (b) either that the sensorimotor impairments observed in autistic children are acquired at a stage when they do not impact on reading acquisition anymore, or that they are in fact of a different nature from those observed in dyslexic children, so that they do not have the same secondary effects on reading. This is certainly a possibility but in the absence of supportive evidence this does not appear to be the most parsimonious explanation.

How likely is it that sensorimotor impairments observed in autistic children are of a different nature from those observed in dyslexic children? It should be recalled that the tasks used here do not tap random aspects of sensorimotor function, but have been chosen precisely because of their presumed capacity to reveal deficits conducive to reading disability according to sensorimotor theories of dyslexia, and because dyslexics have been repeatedly shown to be poor at those tasks. Certainly there are several ways to fail a given task. In the case of autistic children, one might want to argue that they fail because of general intellectual disability, poor task comprehension, or poor executive function that might lead to an inability to concentrate on the sensorimotor tasks. Yet this would not predict the observed pattern, with only a subset of autistic children affected across the whole range of IQ scores and with selective impairments for certain tasks but not others (e.g., motion but not form detection). Furthermore this would beg the question of why those factors that might explain poor autistic performance in sensorimotor tasks would not affect reading ability in the same way.

Sensorimotor impairments may not be able by themselves to explain dyslexia or autism, but it is quite remarkable that they were much more prevalent in both the dyslexic and the autistic than in the control population. Why this is so remains unknown. One possibility is that, rather than being causes of reading (or any other specific cognitive) disability, sensorimotor impairments are more general nonspecific markers of neurodevelopmental disorders. This hypothesis is consistent with the model proposed by Ramus (2004), in which specific cognitive deficits (like dyslexics' phonological deficit) are caused by abnormalities in specific cortical areas, while sensorimotor disorders are secondary, occasional consequences of cortical abnormalities, regardless of their location (hence regardless of the nature of the cognitive deficit). Such a model would seem to be able to explain both the prevalence of sensorimotor impairments in all neurodevelopmental disorders and the absence of any reliable relationship between them and any specific cognitive deficit.

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