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Laterality, hand control and scholastic performance: a British birth cohort study

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ABSTRACT

Objectives: To use simple measures of laterality and hand control that can identify a greater risk of poorer scholastic ability, potentially signalling suboptimal hemispheric lateralisation.

Design: Analysis of material from a birth cohort study.

Setting: Members of the National Child Development Study, a British birth cohort study following people born in 1958.

Participants: 10 612 children who undertook tests at age 11 years.

Primary outcome measures: Teacher-administered tests of non-verbal general ability, verbal general ability, reading comprehension and mathematics.

Results: Linear regression produced associations (and 95% CIs) with tests of verbal general ability, non-verbal general ability, reading comprehension and mathematics scores for the lowest third (compared with highest) of a left-hand control test involving picking up matches of -1.21 (-1.73 to -0.68; $p<0.001$), -0.72 (-1.14 to -0.29; $p=0.001$), -0.70 (-1.06 to -0.35; $p<0.001$) and -1.32 (-1.90 to -0.73; $p<0.001$). Among those in the lowest third of the right-hand control test score, mixed-handedness compared with right-handedness was associated with poorer scholastic performance, with regression coefficients (and 95% CIs; p values) of 1.90 (-3.01 to -0.80; $p=0.001$), -1.25 (-2.15 to -0.35; $p=0.007$), -1.28 (2.04 to -0.53; $p=0.001$) and -1.33 (-2.53 to -0.13; $p=0.030$). The estimates are for a point change in the scholastic test scores, after adjustment for sex, left-hand motor function and social class. Statistically significant associations with mixed-handedness were only observed for the lowest third of right-hand motor function.

Conclusions: Measures involving poorer left-hand motor function may represent useful markers of reduced cognitive function possibly reflecting suboptimal hemispheric lateralisation. Crude measures of laterality such as reported non-right-handedness may be more useful for research when combined with measures of motor function.

ARTICLE SUMMARY

Article focus
■ Some patterns of laterality and hand use can signal atypical brain development before birth relevant to problems with language development and scholastic performance. Measures of left- and right-hand control were investigated as markers of cognitive function and were combined with a crude measure of laterality in an attempt to improve its usefulness as a marker of underlying problems relevant to lateralisation and impaired scholastic performance.

Key messages
■ Poorer results from tests of hand control, particularly for the left side, are associated with lower scholastic test scores.
■ Combining crude measures of laterality with hand control test results may improve their usefulness in research to identify children with potentially suboptimal neurological development.

Strengths and limitations of this study
■ The study benefited from use of a large cohort of children representative of the British general population.
■ The study did not identify the neurological processes responsible, or their causes, only potential markers for use in research.

spheric lateralisation is one of the factors thought to explain these associations.[3–5] Research using a longitudinal birth cohort study in Finland[6] demonstrated that the most notable associations with impaired scholastic ability are among those who are mixed-handed (ambidextrous) rather than left-handed. Unsophisticated measures such as reported right-handedness, left-handedness and mixed-handedness, as used in the Finnish study,[6] are imprecise markers of subtle developmental deficits and may therefore be of limited use in research. This paper is concerned with examining simple measures of laterality and hand control including measures of motor function, which may signal developmental deficits relevant to scholastic ability.

Motor function is associated with ability in both reading and mathematics[7–10] and thus

INTRODUCTION

Non-right-handedness is linked with a raised risk of scholastic and language difficulties, as well as mental health or behavioural problems such as attention-deficit/hyperactivity disorder (ADHD),[1 2] and suboptimal hemi-

a useful indicator of relevant general neurological function. We used a measure of motor function, involving tasks for the left and right hands. The aims of using the motor test scores were to identify children among whom non-right-handedness is a better indicator of poorer scholastic ability and also to examine whether the motor test results themselves provide more useful information than an unsophisticated classification of laterality (left-, right- and mixed-handed where no hand preference was specified).

A British general population-based birth cohort study[11] provided information on laterality, and two tests of motor function for both left and right hand were administered by a doctor at age 11 years: time to pick up 20 matches and number of boxes ticked within a time limit. We chose to use the picking up matches test, as ticking boxes involves writing skills, which could be more influenced by cultural norms for hand preference,[12] and therefore, we hypothesised potentially less precise as a less dominant hand may be used more, thus improving performance. For outcome measures of cognitive or scholastic ability, we used four tests conducted at age 11 years. The main analysis was stratified by level of right-hand motor function (in equal thirds of the distribution). The right hand was chosen as it tends to be the dominant hand.

METHODS
Research setting and study design
A total of 10 612 cohort members from The National Child Development Study (NCDS)[11] were included in the analyses. NCDS is following everyone born between 3 and 9 March 1958 and living in Great Britain, with data collection sweeps at various ages.[13] The study originally comprised approximately 17 000 births, but the subsequent exclusion of Northern Ireland, death, emigration and other causes of attrition reduced the sample size, although the cohort has remained broadly representative of the target population.[14]

Measures
Laterality and hand control
When the children were aged 7 years, mothers were asked if they thought their child was right-handed, left-handed, ambidextrous (mixed handed) or don't know. Local authority medical officers administered a series of functional assessments. The chosen test of motor function was undertaken at age 11 years and recorded the time in seconds that it took to pick up 20 matches (maximum 99 s), separately for left and right hand, with a higher score indicating poorer performance.

Scholastic ability
Teachers administered tests of cognition and scholastic ability at school when the children were 11 years old. These tests were for verbal general ability (score range 0−40), non-verbal general ability (0−40), reading comprehension (0−35) and mathematics (0−40). The tests were constructed specifically for use in NCDS by the National Foundation for Educational Research in England and Wales.[11 15]

Other measures
At age 11 years, local authority medical officers conducted a medical examination and record review, which identified children with a 'general motor handicap' with categories: 'none', 'condition present but no handicap', 'slight handicap', 'moderate handicap' or 'severe handicap'. Social class (Registrar General) based on the father's occupation was categorised as I, II, III non-manual, III manual, IV non-manual, IV manual, V, no father present and 'not assigned' (where there was insufficient information).

Inclusion and exclusion criteria
Information on laterality and the picking up matches test score was available for 11 489 children. Of these, 37 reported uncertain laterality and were excluded. A further 129 were excluded due to missing data on parental social class. From among those remaining, 10 657 completed at least one scholastic ability test, but 45 were excluded due to an observed or diagnosed condition or disability relevant to motor function. Data for 10 612 children were available for the tests of verbal general ability, non-verbal general ability and reading comprehension. Data for 10 608 children were available for the mathematics test.

Statistical analysis
Means and cross-tabulation describe the study population, and this analysis was stratified by laterality. The scores for picking up matches (the marker of motor control) for left and right hands were divided into equal thirds of their distributions.

Linear regression models used test scores as dependent variables: verbal general ability, non-verbal general ability, reading comprehension and mathematics. Analyses were externally stratified by right-hand motor function test thirds (separate analyses for each third). Further analysis combined the two highest right-hand motor function thirds to ensure that statistical significance in the lowest function third could not be explained by greater statistical power. Variables included in the analyses were laterality, *left*-hand motor test score (in thirds), sex and social class. The measures were modelled as series of binary dummy variables, first examined separately and then with mutual simultaneous adjustment.

Interaction testing assessed whether stratification by right-hand motor function modified the associations of laterality with the tests of scholastic ability. Interaction terms (and main effects) were included in non-stratified linear regression models with the measures of scholastic ability as dependent variables. Similar interaction testing examined the combination of left- and right-hand motor

function (in thirds of their distributions due to non-linearity). PASW V.18 software was used.

Ethics

Specific ethical permission was not required for this secondary analysis of anonymised data.

RESULTS

Table 1 shows the population characteristics, presented in separate columns for right-, left- and mixed-handedness. Non-right-handedness was associated with somewhat lower average test scores for general ability (both verbal and non-verbal), reading comprehension and mathematics, with little difference between left- and mixed-handedness.

As expected, left-handed cohort members were more often in the highest third for the left-hand motor function test and the lowest third for the right-hand test. Boys predominate among the left- or mixed-handed. Non-right-handedness is somewhat associated with lower parental social class.

In tables 2–5, results are stratified into thirds of the right-hand motor function test (picking up matches), where the top section of the tables is for those with the poorest performance. The number of subjects in each

stratum and laterality group can be ascertained from table 1.

Verbal general ability

Among those in the lowest right-hand motor function group, left- and particularly mixed-handedness, compared with right-handedness, are statistically significantly and independently associated with lower verbal general ability scores (table 2). Statistically significant associations for laterality were not observed in the two higher thirds for right-hand motor function. Interaction testing provided evidence of effect modification by right-hand motor function for mixed-handedness (p=0.039), but not left-handedness (p=0.980). Lower left-hand motor function test scores were statistically significantly associated with lower verbal general ability scores in the *lowest right-hand stratum*, independent of the potential confounding factors (although interaction testing was not significant). A borderline statistically significantly reduced score for low left-hand function was also observed in the highest right hand function stratum.

Non-verbal general ability

Among those in the lowest right-hand motor function stratum, lower non-verbal general ability scores were

Table 1 Characteristics of the study population divided by hand laterality

	Mean value (SD) or n (%), by hand laterality		
	Right	**Left**	**Mixed**
Mean test score			
Verbal general ability	22.8 (SD 9.2)	21.6 (SD 9.5)	21.4 (SD 9.2)
Non-verbal general ability	21.4 (SD 7.4)	20.6 (SD 7.6)	20.7 (SD 7.6)
Reading comprehension	16.4 (SD 6.2)	15.9 (SD 6.4)	16.0 (SD 6.5)
Mathematics	17.4 (SD 10.3)	16.6 (SD 10.3)	16.3 (SD 10.3)
Right-hand motor score			
Lowest third*	2967 (33.4)	457 (41.7)	272 (36.9)
Middle third	2921 (32.8)	331 (30.2)	235 (31.9)
Highest third	3008 (33.8)	307 (28.0)	230 (31.2)
Left-hand motor score			
Lowest third*	2976 (33.5)	312 (28.5)	238 (32.3)
Middle third	3192 (35.9)	391 (35.7)	260 (35.3)
Highest third	2728 (30.7)	392 (35.8)	239 (32.4)
Sex			
Male	4391 (49.4)	626 (57.2)	446 (60.5)
Female	4505 (50.6)	469 (42.8)	291 (39.5)
Fathers' social class (Registrar General's)			
I	448 (5.0)	52 (4.7)	39 (5.3)
II	1313 (14.8)	150 (13.7)	83 (11.3)
III non-manual	888 (10.0)	91 (8.3)	70 (9.5)
III manual	3853 (43.3)	513 (46.8)	328 (44.5)
IV non-manual	173 (1.9)	11 (1.0)	14 (1.9)
IV manual	1362 (15.3)	161 (14.7)	128 (17.4)
V	541 (6.1)	69 (6.3)	43 (5.8)
Information missing	83 (0.9)	25 (2.3)	8 (1.1)
No male head	235 (2.6)	23 (2.1)	24 (3.3)
Total (row %)	8896 (82.9)	1095 (10.2)	737 (6.9)

*The lowest third of the motor function tests indicates poorest performance (longest time to pick up 20 matches).

Table 2 Verbal general ability test and laterality, stratified by right-hand motor score

	Test score Mean value (SD)	Unadjusted		Adjusted*	
		Coefficient (95% CI)	p Value	Coefficient (95% CI)	p Value
Lowest third† (right hand)					
Laterality					
Right	21.85 (9.28)	Reference		Reference	
Left	20.37 (9.77)	−1.48 (−2.40 to −0.56)	0.002	−1.51 (−2.38 to −0.63)	0.001
Mixed	19.77 (9.14)	−2.08 (−3.23 to −0.92)	<0.001	−1.90 (−3.01 to −0.80)	0.001
Left-hand motor score					
Lowest third†	20.97 (9.45)	−1.46 (−2.77 to −0.15)	0.029	−1.39 (−2.64 to −0.15)	0.028
Middle third	22.52 (9.19)	0.09 (−1.28 to 1.46)	0.901	0.02 (−1.29 to 1.32)	0.981
Highest third	22.43 (8.51)	Reference		Reference	
Middle third (right hand)					
Laterality					
Right	22.84 (9.05)	Reference		Reference	
Left	22.23 (9.18)	−0.61 (−1.65 to 0.42)	0.244	−0.16 (−1.16 to 0.83)	0.749
Mixed	22.06 (9.22)	−0.79 (−1.99 to 0.42)	0.202	−0.33 (−1.48 to 0.83)	0.577
Left-hand motor score					
Lowest third†	22.10 (8.91)	−0.76 (−1.63 to 0.10)	0.083	−0.58 (−1.41 to 0.25)	0.169
Middle third	23.01 (9.18)	0.15 (−0.62 to 0.92)	0.707	0.27 (−0.47 to 1.01)	0.477
Highest third	22.86 (9.03)	Reference		Reference	
Highest third (right hand)					
Laterality					
Right	23.77 (9.05)	Reference		Reference	
Left	22.85 (9.08)	−0.91 (−1.98 to 0.15)	0.092	−0.92 (−1.94 to 0.09)	0.074
Mixed	22.62 (8.98)	−1.14 (−2.36 to 0.07)	0.065	−0.74 (−1.89 to 0.42)	0.210
Left-hand motor score					
Lowest third†	22.50 (8.83)	−1.36 (−2.72 to 0.00)	0.050	−1.33 (−2.62 to 0.05)	0.042
Middle third	23.22 (8.91)	−0.64 (−1.31 to 0.04)	0.064	−0.45 (−1.09 to 0.19)	0.171
Highest third	23.86 (9.12)	Reference		Reference	

*Adjusted for laterality, left-hand motor score, sex and parental social class.
†The lowest third of the motor function tests indicates poorest performance (longest time to pick up 20 matches).

statistically significantly and independently associated with left- and particularly mixed-handedness compared with right-handedness (table 3). Non-right-handedness was not statistically significantly associated with the verbal general ability scores in the two higher right-hand motor function strata. Interaction testing provided evidence of effect modification by right-hand motor function for mixed-handedness (p=0.012), but not left-handedness (p=0.786).

Lower left-hand motor function test scores were statistically significantly associated with lower verbal general ability scores in the *lowest right-hand performance third*, independent of the potential confounding factors. Interaction testing suggests effect modification for the combination of low left-hand function with low right function (p=0.007).

Reading comprehension
Among those in the lowest right-hand motor function stratum, lower reading comprehension scores were associated with mixed-handedness compared with right-handedness (table 4). After adjustment, the associations with both left- and mixed-handedness were statistically significant. Non-right-handedness was not statistically significantly associated with the reading comprehension scores in the two higher right-hand performance strata.

Interaction testing provided evidence of effect modification by right-hand motor function for mixed-handedness (p<0.001), but not left-handedness (p=0.598).

Lower left-hand motor function test scores were statistically significantly associated with lower reading comprehension scores in the *lowest and highest* right-hand performance thirds, independent of the potential confounding factors (although interaction testing was not statistically significant).

Mathematics
Among those in the lowest right-hand motor function stratum, lower test scores were associated with left- and particularly mixed-handedness compared with right-handedness (table 5).

These associations were statistically significant and independent of the potential confounding factors. Non-right-handedness was not statistically significantly associated with the mathematics test scores in the two higher right-hand performance strata. Interaction testing did not provide strong evidence of effect modification by right-hand motor function for mixed-handedness (p=0.195) or left-handedness (p=0.810).

Lower left-hand motor function test scores were statistically significantly associated with lower mathematics test scores in the *lowest and highest* right-hand

Table 3 Non-verbal general ability test and laterality, stratified by right-hand motor score

	Test score Mean value (SD)	Unadjusted		Adjusted*	
		Coefficient (95% CI)	p Value	Coefficient (95% CI)	p Value
Lowest third† (right hand)					
Laterality					
Right	20.69 (7.57)	Reference		Reference	
Left	19.74 (7.88)	−0.95 (−1.70 to −0.20)	0.013	−1.05 (−1.77 to −0.34)	0.004
Mixed	19.42 (7.60)	−1.27 (−2.22 to −0.33)	0.008	−1.25 (−2.15 to −0.35)	0.007
Left-hand motor score					
Lowest third†	20.01 (7.76)	−1.13 (−2.19 to −0.06)	0.038	−0.99 (−2.01 to 0.03)	0.056
Middle third	21.38 (7.34)	0.25 (−0.87 to 1.36)	0.663	0.27 (−0.79 to 1.33)	0.620
Highest third	21.14 (7.01)	Reference		Reference	
Middle third (right hand)					
Laterality					
Right	21.40 (7.33)	Reference		Reference	
Left	20.92 (7.55)	−0.48 (−1.31 to 0.36)	0.266	−0.18 (−0.99 to 0.63)	0.665
Mixed	21.05 (7.71)	−0.35 (−1.33 to 0.63)	0.479	−0.12 (−1.07 to 0.82)	0.796
Left-hand motor score					
Lowest third†	21.09 (7.14)	−0.21 (−0.91 to 0.49)	0.558	−0.02 (−0.69 to 0.66)	0.963
Middle third	21.48 (7.47)	0.18 (−0.45 to 0.80)	0.577	0.30 (−0.31 to 0.90)	0.335
Highest third	21.30 (7.45)	Reference		Reference	
Highest third (right hand)					
Laterality					
Right	22.24 (7.24)	Reference		Reference	
Left	21.55 (7.13)	−0.69 (−1.54 to 0.16)	0.111	−0.79 (−1.60 to 0.03)	0.058
Mixed	21.77 (7.36)	−0.48 (−1.45 to 0.49)	0.335	−0.33 (−1.26 to 0.59)	0.480
Left-hand motor score					
Lowest third†	21.64 (7.17)	−0.67 (−1.76 to 0.41)	0.224	−0.64 (−1.68 to 0.39)	0.220
Middle third	21.87 (7.20)	−0.44 (−0.98 to 0.10)	0.106	−0.27 (−0.78 to 0.24)	0.301
Highest third	22.31 (7.26)	Reference		Reference	

*Adjusted for laterality, left-hand motor score, sex and parental social class.
†The lowest third of the motor function tests indicates poorest performance (longest time to pick up 20 matches).

performance thirds, independent of the potential confounding factors. Interaction testing did not identify effect modification (p>0.05).

In further analyses, the two higher right-hand motor function score thirds were combined to ensure that the statistical significance of associations of laterality with the scholastic test scores in the lowest right-hand motor function stratum were not due to greater statistical power. Neither left- nor mixed-handedness is statistically significantly associated with any of the scholastic tests in the combined top two thirds for right-hand motor function (data not shown). There were no notable gradients in the association of laterality with the scholastic test scores across the two higher right-hand motor function strata. Although the average scholastic test scores tended to be lower among those who were mixed-handed than for left-handedness, no statistically significant differences were observed when mixed-handedness was compared with left-handedness.

Non-stratified analysis
Table 6 shows associations with each of the four scholastic tests for laterality, right-hand motor function and left-hand motor function test scores. Right-handedness and the highest third of the motor function tests were

used as reference categories. In the adjusted models, non-right-handedness was associated with statistically significantly poorer scholastic ability, except for the reading comprehension test. It is notable that cohort members with left-hand motor scores in lowest third had lower average scholastic test scores than those with parentally reported non-right-handed laterality. Poorer left-hand function was associated with lower average scholastic scores than poorer right-hand function, except for non-verbal general ability where low right-hand function was associated with somewhat lower scores.

The online appendix presents the results of further analyses showing similar associations, where the motor function test involved ticking boxes rather than picking up matches.

DISCUSSION
Although the a priori hypothesis for this study involved the combination of lack of reported hand preference (described as 'mixed-handedness') with a measure of right-hand motor function, the measures of left- and right-hand motor function themselves may have produced more informative results. Poorer motor function in both hands, but particularly the left, was

Table 4 Reading comprehension test and laterality, stratified by right-hand motor score

	Test score Mean value (SD)	Unadjusted Coefficient (95% CI)	p Value	Adjusted* Coefficient (95% CI)	p Value
Lowest third† (right hand)					
Laterality					
Right	15.91 (6.42)	Reference		Reference	
Left	15.34 (6.74)	−0.57 (−1.21 to 0.07)	0.081	−0.64 (−1.24 to −0.04)	0.036
Mixed	14.52 (6.46)	−1.39 (−2.19 to −0.58)	0.001	−1.28 (−2.04 to −0.53)	0.001
Left-hand motor score					
Lowest third†	15.40 (6.59)	−1.19 (−2.10 to −0.29)	0.010	−1.05 (−1.91 to −0.20)	0.016
Middle third	16.32 (6.27)	−0.27 (−1.22 to 0.68)	0.581	−0.26 (−1.15 to 0.64)	0.571
Highest third	16.59 (5.91)	Reference		Reference	
Middle third (right hand)					
Laterality					
Right	16.36 (6.06)	Reference		Reference	
Left	16.02 (6.07)	−0.34 (−1.03 to 0.36)	0.341	−0.10 (−0.76 to 0.56)	0.763
Mixed	16.49 (6.53)	0.14 (−0.67 to 0.95)	0.737	0.32 (−0.45 to 1.09)	0.414
Left-hand motor score					
Lowest third†	16.00 (5.98)	−0.48 (−1.06 to 0.10)	0.106	−0.28 (−0.83 to 0.27)	0.324
Middle third	16.45 (6.20)	−0.03 (−0.55 to 0.49)	0.912	0.10 (−0.39 to 0.60)	0.677
Highest third	16.48 (5.99)	Reference		Reference	
Highest third (right hand)					
Laterality					
Right	16.86 (5.94)	Reference		Reference	
Left	16.73 (6.20)	−0.12 (−0.83 to 0.58)	0.732	−0.21 (−0.87 to 0.46)	0.539
Mixed	17.11 (6.13)	0.25 (−0.55 to 1.05)	0.536	0.35 (−0.40 to 1.11)	0.360
Left-hand motor score					
Lowest third†	16.07 (5.85)	−0.95 (−1.84 to −0.05)	0.038	−0.90 (−1.75 to −0.06)	0.036
Middle third	16.64 (5.99)	−0.37 (−0.81 to 0.08)	0.105	−0.20 (−0.62 to 0.22)	0.353
Highest third	17.01 (5.98)	Reference		Reference	

*Adjusted for laterality, left-hand motor score, sex and parental social class.
†The lowest third of the motor function tests indicates poorest performance (longest time to pick up 20 matches).

associated with poorer scholastic ability. The combination of poor left-hand motor function with either low or high right-hand function was associated with lower average test scores. Non-right-handedness alone was not notably associated with poorer scholastic ability; only the combination of non-right-handedness and lower right hand motor function (the lowest third) was consistently associated with poor scholastic ability. Interaction testing indicated effect modification for the specific combination of no reported hand preference and poorer motor performance.

A previous study demonstrated an association between 'mixed-handedness' (lack of reported hand preference) and poorer scholastic performance, where laterality was reported by parents using a single-item question.[6] For comparability, we also used parent-reported laterality but combined this with left- and right-hand motor function tests. Associations of motor function[16−18] and laterality[6−10] with intelligence and scholastic ability have been demonstrated previously, but this combination of motor function with this measure of handedness in the general population is more novel. Studies of laterality often use a series of questions for more precise classification,[19−21] rather than the single question used by this study which limits accuracy significantly. A more elaborate approach also allows grading of strength of left- or right-handedness. A lack of reported hand preference may reflect uncertainty about laterality,[19] so a more precise instrument should reduce the misclassification that is likely to have existed in our study. For this reason, our 'mixed-handed' group may be heterogeneous, and the results using parent-reported handedness should be interpreted with caution. Despite this imprecision, interpretability of the results may have been increased by our use of more objective left- and right-hand motor function measures. Although imprecise, the laterality measure used here can be compared with other studies that have used a similar simple measure. Non-right-handedness among the lowest right-hand motor function group may help to identify a *small* subgroup at greater risk of having suboptimal hemispheric lateralisation.

Motor function is associated with cognitive ability,[7−10] and a striking feature of our findings is the magnitude of the association of poor left hand motor function with worse scholastic test scores. Interestingly, the combination of low left-hand function with either low or high right-hand function was associated with lower scholastic test scores. This is consistent with Marian Annett's right shift theory of handedness and cerebral dominance,

Table 5 Mathematics test and laterality, stratified by right-hand motor score

	Test score Mean value (SD)	Unadjusted Coefficient (95% CI)	p Value	Adjusted* Coefficient (95% CI)	p Value
Lowest third† (right hand)					
Laterality					
Right	16.35 (10.28)	Reference		Reference	
Left	15.42 (10.33)	−0.93 (−1.95 to 0.08)	0.071	−1.12 (−2.07 to −0.17)	0.021
Mixed	14.96 (10.29)	−1.39 (−2.67 to −0.11)	0.034	−1.33 (−2.53 to −0.13)	0.030
Left-hand motor score					
Lowest third†	15.57 (10.30)	−1.56 (−3.00 to −0.12)	0.034	−1.26 (−2.62 to 0.09)	0.067
Middle third	17.17 (10.35)	0.05 (−1.46 to 1.56)	0.951	0.15 (−1.27 to 1.57)	0.834
Highest third	17.13 (9.50)	Reference		Reference	
Middle third (right hand)					
Laterality					
Right	17.47 (10.14)	Reference		Reference	
Left	17.01 (10.54)	−0.46 (−1.61 to 0.70)	0.440	−0.22 (−1.32 to 0.89)	0.699
Mixed	16.63 (10.18)	−0.84 (−2.19 to 0.52)	0.226	−0.60 (−1.88 to 0.68)	0.360
Left-hand motor score					
Lowest third†	16.62 (9.86)	−1.06 (−2.03 to −0.09)	0.033	−0.77 (−1.69 to 0.15)	0.102
Middle third	17.63 (10.24)	−0.05 (−0.91 to 0.81)	0.912	0.14 (−0.68 to 0.96)	0.743
Highest third	17.68 (10.38)	Reference		Reference	
Highest third (right hand)					
Laterality					
Right	18.36 (10.28)	Reference		Reference	
Left	17.79 (9.94)	−0.57 (−1.78 to 0.63)	0.352	−0.77 (−1.91 to 0.36)	0.180
Mixed	17.65 (10.29)	−0.71 (−2.09 to 0.66)	0.310	−0.61 (−1.90 to 0.68)	0.352
Left-hand motor score					
Lowest third†	16.64 (10.51)	−1.93 (−3.47 to −0.39)	0.014	−1.73 (−3.27 to −0.40)	0.012
Middle third	17.84 (10.10)	−0.73 (−1.49 to 0.03)	0.060	−0.45 (−1.16 to 0.27)	0.221
Highest third	18.57 (10.28)	Reference		Reference	

*Adjusted for laterality, left-hand motor score, sex and parental social class.
†The lowest third of the motor function tests indicates poorest performance (longest time to pick up 20 matches).

where hypothetical genetic factors produce a continuum of hemispheric asymmetry.[22] A lack of asymmetry may be detrimental for some aspects of hemispheric specialisation, but excessive asymmetry (as signalled by high right- and low left-hand motor function) may also limit some functions relevant to cognition and behaviour.[22] Strong right-handedness has been linked with poorer cognitive function, including for episodic memory.[23–25]

In addition to stratifying by right hand motor function and adjusting for left hand motor function, we adjusted for several other measures to ensure that the results were not due to confounding. We adjusted for sex as it is associated with laterality, motor control and scholastic ability.[26 27] We also included parental social class to improve precision, as there are social influences on learning and problem solving.[28] To ensure that the results are not influenced by a small group of children with disabilities, children with any diagnosed motor disabilities were excluded from the analysis. We did not adjust for developmental factors, as the study was designed to examine measures of handedness, rather than identify causes.

While this study cannot identify the neurological mechanisms underlying associations between laterality or hand control and scholastic performance, suboptimal hemispheric lateralisation is one possible component of the explanation. Task specialisation between the left and right hemispheres can be associated with cerebral asymmetry in anatomy, neurotransmitter expression and inter-hemispheric signalling.[29–31] A high degree of lateralisation in function may result in, or be influenced by, higher level cognitive function.[32] Abnormalities in cerebral asymmetry and inter-hemispheric signalling have been associated with developmental and behavioural problems such as ADHD,[4] so related difficulties may help explain our findings. Boys appear to be particularly susceptible to in utero exposures relevant to suboptimal lateralisation, as premature boys are at greater risk of non-right-handedness and behavioural disorders like ADHD.[33 34] A consistent finding is that more of the boys in this study were non-right-handed. Functional cortical asymmetry can vary with age,[30] indicating that later life exposures may influence whether suboptimal lateralisation persists.

Potential limitations of this study include the imprecise laterality measure reported by mothers, particularly as the 'mixed-handed' category reflects no reported hand preference rather than a more structured assessment of whether an individual is ambidextrous. Division of the motor function scores into equal thirds may not be optimal but chosen on an a priori basis to demonstrate a constant pattern with the minimum number of

Table 6 Non-stratified analysis of associations with each of the four scholastic tests, for laterality and the hand motor function tests

	Test score Mean value (SD)	Unadjusted Coefficient (95% CI)	p Value	Adjusted* Coefficient (95% CI)	p Value
Verbal score					
Laterality†					
Left	21.63 (9.46)	−1.19 (−1.77 to −0.62)	<0.001	−0.91 (−1.46 to −0.36)	0.001
Mixed	21.39 (9.19)	−1.43 (−2.12 to −0.74)	<0.001	−1.03 (−1.69 to −0.38)	0.002
Left-hand motor score‡					
Lowest third	21.36 (9.29)	−2.19 (−2.62 to −1.75)	<0.001	−1.21 (−1.73 to −0.68)	<0.001
Middle third	22.92 (9.11)	−0.62 (−1.04 to −0.19)	0.004	−0.12 (−0.56 to 0.33)	0.610
Right-hand motor score‡					
Lowest third	21.51 (9.35)	−2.10 (−2.52 to −1.68)	<0.001	−0.84 (−1.35 to −0.32)	0.001
Middle third	22.73 (9.08)	−0.88 (−1.31 to −0.46)	<0.001	−0.30 (−0.75 to 0.15)	0.192
Non-verbal score					
Laterality†					
Left	20.61 (7.61)	−0.84 (−1.31 to −0.38)	<0.001	−0.70 (−1.15 to −0.25)	0.002
Mixed	20.67 (7.62)	−0.78 (−1.34 to −0.22)	0.006	−0.60 (−1.13 to −0.07)	0.027
Left-hand motor score‡					
Lowest third	20.39 (7.58)	−1.62 (−1.97 to −1.27)	<0.001	−0.72 (−1.14 to −0.29)	0.001
Middle third	21.55 (7.37)	−0.46 (−0.80 to −0.11)	0.009	0.05 (-0.32 to 0.41)	0.799
Right-hand motor score‡					
Lowest third	20.48 (7.62)	−1.67 (−2.01 to −1.33)	<0.001	−0.91 (−1.33 to −0.49)	<0.001
Middle third	21.33 (7.38)	−0.82 (−1.17 to −0.47)	<0.001	−0.47 (−0.84 to −0.10)	0.012
Reading ability score					
Laterality†					
Left	15.94 (6.42)	−0.44 (−0.83 to −0.05)	0.027	−0.33 (−0.70 to 0.04)	0.078
Mixed	15.96 (6.47)	−0.42 (−0.88 to 0.05)	0.079	−0.27 (−0.71 to −0.16)	0.221
Left-hand motor score‡					
Lowest third	15.59 (6.40)	−1.27 (−1.56 to −0.98)	<0.001	−0.70 (−1.06 to −0.35)	<0.001
Middle third	16.46 (6.17)	−0.40 (−0.69 to −0.12)	0.006	−0.09 (−0.39 to 0.21)	0.544
Right-hand motor score‡					
Lowest third	15.74 (6.48)	−1.12 (−1.41 to −0.84)	<0.001	−0.41 (−0.76 to −0.07)	0.019
Middle third	16.33 (6.10)	−0.53 (−0.82 to −0.24)	<0.001	−0.18 (−0.48 to 0.13)	0.256
Mathematics test score					
Laterality†					
Left	16.56 (10.33)	−0.83 (−1.48 to −0.19)	0.011	−0.70 (−1.31 to −0.10)	0.023
Mixed	16.33 (10.31)	−1.06 (−1.83 to −0.29)	0.007	−0.87 (−1.60 to −0.15)	0.018
Left-hand motor score‡					
Lowest third	15.91 (10.20)	−2.36 (−2.85 to −1.88)	<0.001	−1.32 (−1.90 to −0.73)	<0.001
Middle third	17.55 (10.24)	−0.72 (−1.19 to −0.25)	0.003	−0.17 (−0.67 to 0.32)	0.499
Right-hand motor score‡					
Lowest third	16.13 (10.30)	−2.13 (−2.60 to −1.66)	<0.001	−0.88 (−1.45 to −0.32)	0.002
Middle third	17.37 (10.18)	−0.90 (−1.38 to −0.42)	<0.001	−0.28 (−0.78 to 0.22)	0.275

*Adjusted for laterality, left-hand motor score, right-hand motor score, sex and parental social class.
†Right-handed as the reference category.
‡The lowest third of the motor function tests indicates poorest performance (longest time to pick up 20 matches). The highest third is used as the reference category.

groups. To ensure that differences in statistical power did not account for the findings, the two higher function thirds were combined and statistical significant association for mixed handedness were still only observed in the lowest function third. A limitation of the stratified design is that it could underestimate the overall magnitude of associations with scholastic test scores. The cohort remained largely representative of the general population, but loss of the most disadvantaged children[35] may have limited participation of some children with the poorest scholastic performance. The tests used

here cannot identify causes or underlying mechanisms and these may be heterogeneous.

CONCLUSIONS
Simple objective tests of left- and right-hand motor function may be used to produce more useful markers of neurological characteristics relevant to scholastic performance than crude reports of left-handedness, right-handedness or where no hand preference is reported. If a crude measure of laterality is all that is available, combining it with a measure of objective motor

function may improve its utility. The notably worse scholastic scores associated with poor left-hand function suggest that this may be a useful measure alone or in combination with others.

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