

# The development of handedness in children

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*Direction and degree of handedness were assessed in children aged 3 to 9 years old, in transverse and longitudinal studies, using a 10-item performance battery. Item analysis revealed a single underlying factor with a bimodal distribution. Direction of handedness appears to be more or less fixed by the age of 3. Degree of handedness increases at least over the range 3 to 7 years, and perhaps more slowly from 7 to 9. Degree of handedness increased more rapidly in left-handers than in right-handers. Degree of handedness showed no correlation with reading ability or general intelligence. The theoretical implications of these findings are discussed, and interpreted in terms of a hypothesis whereby degree of handedness is a phenomenon sui generis.*

The majority of the adult population is strongly right-handed. However infants do not show any obvious correlates of adult handedness, despite showing a range of subtle and ephemeral asymmetries (e.g. Darwin, 1877), Young, Segalowitz, Corter, & Trehub, 1983). In this paper we delimit the ages during which handedness becomes apparent, considering *direction* and *degree* of handedness in transverse and longitudinal studies. At a more general level the studies consider the broader question of whether cerebral lateralization increases during development (see Curtiss, 1985, for a review).

In recent years it has become apparent that the straightforward classification of the handedness of individuals into two groups, right and left, does not adequately reflect the complexity of the phenomenon. Improvement, however, is controversial. One view is that lateralization is a continuum, approximately normally distributed, with a

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single peak, and that the criterion for division into right- and left-handers is essentially arbitrary (e.g. Annett, 1985a). Alternatively, handedness can be regarded as a mixture of two normal distributions, whether the population distribution is unimodal or bimodal depending upon the separation of the distributions relative to their variances (McManus, 1983a). If the subdistributions are widely separated then two independent measures of laterality can be calculated: direction of lateralization, which is categorical, having two levels, left and right, and degree of lateralization, which is continuous. If a conventional laterality coefficient such as  $(R - L)/(R + L)$  is calculated then degree of lateralization is the absolute laterality coefficient and direction is the sign of the laterality coefficient. If handedness is a mixture then simple use of a signed laterality coefficient can produce highly misleading statistical results (McManus, 1983a). The mere presence of unimodality does not exclude the possibility of an underlying mixture of distributions (see McManus, 1982, 1985a).

A theoretical point is that many researchers freely interchange the terms *degree* and *consistency* of handedness. Strictly the terms are separate. Degree refers to the extent to which the two hands are each used for a range of tasks. Consistency refers to the reliability with which each task is carried out by the same hand. A weak right-hander will use the right hand for marginally more tasks than the left hand; if consistent they will always use the same hand for a particular task, whereas if inconsistent will sometimes use the right and sometimes the left hand for a task, but on aggregate will use the right hand more than the left. Aggregate scores derived from questionnaires or performance batteries do not usefully separate these two measures.

Hand *preference* can be assessed by inventory or by performance of specific tasks. Inventory measures are effective with adults (Oldfield, 1969, 1971) and can be short and reliable (Bryden, 1977). Preferences of young children can only be obtained by performance measures. In adults both performance and inventory measures of *preference* usually show either a J-shaped distribution (Annett, 1972), or two separate distributions, the precise shape depending on the number of items in the inventory (McManus, 1979). Performance of skilled tasks produces single mode distributions of laterality scores (e.g. Annett & Kilshaw, 1985) although these can conceal evidence of mixing (McManus, 1985a); see Annett (1985b) and McManus (1985b) for a continuation of this debate.

What factors cause individuals to differ in *direction* and *degree* of lateralization? The former question has been extensively investigated (e.g. Beaton, 1985; Bryden, 1982; Hardyck & Petrionovich, 1977; Porac & Coren, 1981), and there seems little doubt that direction of lateralization is familial (McManus, 1985c). The lack of reliable evidence for environmental correlates, such as birth stress (Beaton, 1985), or childhood head injury (McManus, 1983b), the existence of a stronger correlation of offspring handedness with biological rather than with adoptive parent handedness (Carter-Saltzman, 1980), and evidence for lateralization even in neonates and young infants (see Young *et al.*, 1983) suggest that a genetic factor might be responsible (Annett, 1985a; Levy, 1976; McManus, 1984, 1985c). In comparison there has been little work on the origins of *degree* of handedness. Leiber & Axelrod (1981) found only 'miniscule' evidence for an effect of 'incidental intra-familial modelling', suggesting an absence of environmental influences, and McManus (1985c) found no correlation of *degree* of handedness between parents and children suggesting the

absence of a genetic mechanism. Brooker, Lehman, Heinbuch, & Kidd (1981) found no evidence for genetic control of *degree* of handedness in Bonnett monkeys. Conversely Collins (e.g. 1970), studying 'pawedness' in inbred mice, found no evidence at all for genetic control of *direction* of pawedness, but has suggested that *degree* of pawedness is influenced both by environmental factors (Collins, 1975, 1977) and by genetic factors (Collins, 1981, 1985). In addition, more strongly lateralized mice have larger and more asymmetric brains and differ in their spontaneous behaviours (Ward & Collins, 1985; Ward, Giguere, & St.-Yves, 1986). A genetic basis is also supported by the correlation of *degree* of laterality with the H2 immune recognition system (Collins, Carlson, & Nadeau, 1985). While these animal findings do not necessarily project on to human subjects, the clear asymmetry for language control in the brain and suggestions that the strongly left-handed are more likely to show right-hemisphere control of language (e.g. Dee, 1971) suggest a mechanism too rigid to be shaped by environmental factors alone (see Bradshaw, 1980, for a review of the debate). A firm morphological basis for differences in degree of asymmetry might be found in work such as that of Ratcliff, Dila, Taylor & Milner (1980). Taking all the evidence together, in conjunction with the biological necessity of continuity in evolution, suggests that genetic factors may be of some importance in determining degree of lateralization.

Studies on handedness development in children are confusing, principally because of confusion of *direction* and *degree* of handedness. A typical result is that of Boklage (1981) who reports the handedness at different ages in terms of 'right', 'left or ambi' or 'unknown'. Although the proportion of right-handers rises until about the age of 7 when it becomes static, the criterion for differentiating right and left is not clear, and the results may be explained in terms of change in *degree* of lateralization as much as in *direction*. A similar criticism can be made of the work of Fennell, Satz & Morris (1983). The data are nonetheless in agreement with those of Hardyck, Goldman & Petrinovich (1975), and Roszkowski, Snelbecker, & Sacks, (1980) in transverse studies, and Sinclair (1971) and McManus (1981) in longitudinal studies, which suggest little change in *direction* of handedness from 6 to 19. Earlier studies (e.g. Gesell & Ames, 1947 Hildreth, 1949) and recent reviews (Young *et al.*, 1983) have suggested that handedness is poorly defined in children below the age of 2. Life-span development of handedness is also complicated. Although some studies (e.g. Porac & Coren, 1981) find increased dextrality from 8 to 80, there are no longitudinal studies, and transverse studies are strongly confounded by secular trends in left-handedness during the lifetime of adult subjects (see Porac & Coren, 1981).

This study asks whether *direction* or *degree* of handedness, or both, are changing as children grow older. Batheja & McManus (1985) looked at handedness in normal and mentally handicapped children, and found a clear difference between groups in *direction* of handedness, left-handedness being more common in the handicapped (explained as due to early *in utero* disruption of lateralization). Mentally handicapped children were also less strongly lateralized; Batheja & McManus (1985) hypothesized that *degree* of lateralization is primarily a function of learned experience with an asymmetric world, such experience being both more common (because of emphasis upon reading and writing) and also more salient (because of increased cognitive capacity) in normal children. If correct, children should become more lateralized as

they grow older, particularly over the age range 5 to 7 when they are learning to write, and *degree* of lateralization should correlate with intelligence and with experience of reading and writing. The present studies examined these hypotheses, looking at children aged 3 to 7 in transverse and longitudinal studies, and examining correlations between laterality and achievement in children aged 5 to 9.

## Study 1

### Method

Four groups of children were examined, aged 3 ( $n=60$ ), 4 ( $n=46$ ), 5 ( $n=103$ ) and 7 ( $n=105$ ), 47, 41, 55 and 50 per cent of each sample being male. Children attended primary or nursery schools administered by the Inner London Education Authority (ILEA) and were examined individually while at school. Each child sat at a table opposite an examiner (D.R.C., A.F.M. and J.W.), and tests were administered in a fixed order. Twenty children aged 5 or 7 were assessed twice by separate examiners (D.R.C. and A.F.M.). Ten tasks were used, similar to those of Batheja & McManus (1985), and akin to those of Tan (1985).

- ✓ 1. Drawing: subjects asked to draw a face using a felt-tipped pen.
- ✓ 2. Writing: subjects asked to write name next to the picture.
- 3. Throwing a ball: pick up a ball placed centrally on the table and throw it to examiner.
- 4. Threading beads: subjects threaded three beads on a wire held by the examiner in both hands.
- ✓ 5. Dealing cards: three playing cards placed centrally on the table and children asked to turn them over, one at a time.
- ✓ 6. Spoon: subjects given spoon and asked to show how they ate their breakfast.
- ✓ 7. Toothbrush: subjects asked to pretend to show how they cleaned their teeth.
- ✓ 8. Comb: subjects given a comb and asked to comb their hair.
- ✓ 9. Blowing nose: tissue provided and subjects asked to show how they blow their nose.
- ✓ 10. Picking sweet: subjects asked to take a sweet from a centrally placed bag. Repeated three times.

Children aged 3 or 4 who were unable to write were asked on item 2 to colour a pre-drawn square on a sheet of paper.

The examiner recorded the hand used for each task as Right (R), Left (L), Both (B) if the hands were used bimanually, or Mixed (M) if different hands were used for task repetitions. For analysis, categories M and B were merged as composite category M-B.

### Results

*Factor analysis.* The necessary preconditions for analysing *direction* and *degree* of handedness are that the items should be unidimensional and showing clear bimodality without substantial overlap. The responses of the 314 children in Study 1, marginal distributions of which are shown in Table 1, were correlated, scoring -1 for L, 0 for M-B, and 1 for R, with means substituted for the occasional missing values (due to the child not performing the task appropriately: 0.95 per cent of observations were missing, the greatest incidence being for item 10, 'taking a sweet', where 3 per cent of responses were missing). Principal component factor analysis of the correlation matrix produced eigenvalues of 5.46, 0.92, 0.73, 0.67, 0.57, 0.52, 0.36, 0.32, 0.31, and 0.15, a 'scree slope' criterion (Cattell, 1966) suggesting a single major factor accounting for 54.6 per cent of the total variance. Items 1, 2, 4, 6, 7 and 8 show particularly high loadings on the single factor (Table 1), although all loadings are strongly positive, the minimum being 0.457.

**Table 1.** The result of three separate factor analyses of the data from 444 children

Item	%L	%M-B	Principal component analysis	NOHARM analysis (R vs. M-B and L)		NOHARM analysis (R and M-B vs. L)	
			Loading	Thres.	Discrim.	Thres.	Discrim.
1 Drawing face	12.4	0.3	0.843	1.137	<sup>a</sup>	1.153	<sup>a</sup>
2 Write name or colour square	14.0	0.3	0.879	1.064	<sup>a</sup>	1.078	<sup>a</sup>
3 Throw ball	12.8	10.9	0.710	0.979	1.078	1.271	2.003
4 Thread 3 beads	13.4	10.5	0.804	0.830	0.830	1.630	<sup>a</sup>
5 Turn 3 cards	16.7	34.1	0.457	-0.027	0.746	2.130	0.511
6 Use spoon	13.8	0.6	0.791	1.097	3.932	1.137	3.437
7 Clean teeth	13.9	0.6	0.805	1.081	5.297	1.110	5.395
8 Use comb	11.6	1.0	0.799	1.188	3.970	1.200	<sup>a</sup>
9 Blow nose	14.0	11.4	0.635	1.071	0.810	1.317	1.479
10 Take sweet	19.1	0.0	0.543	1.337	0.860	1.265	0.951
Max  residual					0.0203		0.0227
Median  residual					0.0029		0.0049
Pseudo-chi-squared					4.645		8.313

<sup>a</sup> Infinite discrimination parameter.

Since the distributions of items are not normally distributed, a conventional factor analysis might be inappropriate. Non-linear factor analysis, typically used for psychometric test evaluation, was therefore carried out using NOHARM (Fraser, undated), items being given binary scores, and being assumed to load upon an underlying latent factorial structure (McDonald, 1982). Two scores are calculated for each item: a threshold, indicating, on a cumulative normal distribution scale, the value at which 50 per cent of the population would be scored positive, and a discrimination index, equivalent to the factor loadings in a conventional factor analysis (Lord, 1952). Table 1 shows analyses in which either a response of M-B or L was scored as positive, or only a response of L was scored as positive. Goodness-of-fit was assessed from the median and maximum absolute residuals in the moment matrix, and from a pseudo-chi-squared value calculated from the summed chi-squared values derived from observed and expected proportions in each lower off-diagonal cell of the moment matrix. All items show positive discriminations, and items 1, 2, 5 and 9 have some infinite discrimination parameters, suggesting perfect discrimination between two implicit groups. The separate item analyses show that the three measures of goodness-of-fit all suggest a slightly better fit when M-B responses are scored with L rather than R, implying that mixed or bilateral responses are best regarded as indicators of left-handedness.

*Inter-rater reliability.* Twenty children (10 5-year-olds and 10 7-year-olds), all right-handed at first assessment by D.R.C. or A.F.M. were reassessed later by the other tester to assess the reliability of *degree* of handedness. Assessors did not differ in mean scores (Wilcoxon test, n.s.; paired *t* test,  $t=0.730$ , n.s.), nor in variances ( $F=1.473$ , d.f. = 19, 19, n.s.). Spearman and Pearsonian correlations were  $r=0.939$ , d.f. = 18,  $P<0.001$  and  $r=0.630$ ,  $P<0.002$ , suggesting adequate reliability.

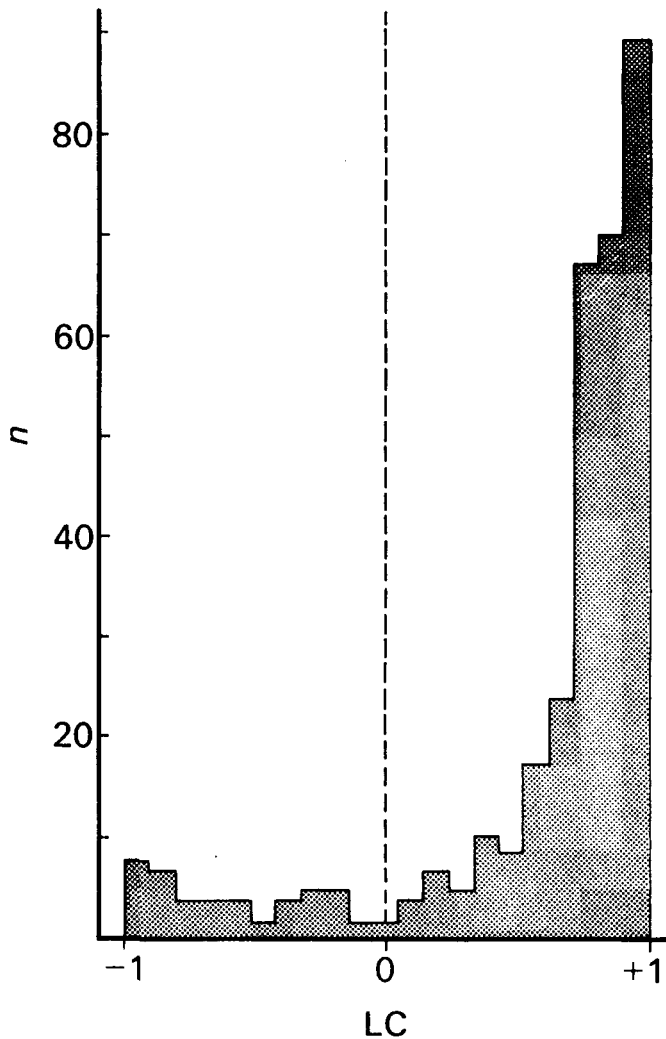
*Composite scores.* Because of the single underlying factor, and the high loadings and discriminations of all items, a composite score was calculated for each subject, using a conventional laterality index (LI)

$$LI = \frac{n(R) - n(L)}{n(R) + n(M-B) + n(L)},$$

where  $n(R)$  is the number of R responses,  $n(L)$  the number of L responses, and  $n(M-B)$  the number M-B responses made by the child. Although this index apparently ignores M-B responses, they are actually weighted midway between right and left responses (weighted 1 and  $-1$ ), and hence they disappear from the formula. A child with many M-B responses will therefore have a low absolute LI, as should be the case since the child is indeed less lateralized. Like all composite scores the formula does not differentiate between the ways in which an index can be generated: in particular it does not distinguish two children with LI scores of zero, one responding M-B to all items, and the other responding 50 per cent R and 50 per cent L. The distribution of laterality indices (Fig. 1) shows a typical J-shaped distribution, with a central minimum, suggesting two separate distributions with little overlap. Scores for *direction* and *degree* of lateralization were calculated for each subject; those scoring greater than zero were classed as right-handers, and *degree* of lateralization was taken as the absolute value of the LI (range = 0 to 1).

It might be objected that Fig. 1 does not show compelling evidence of bimodality because of the small sample size in the left-handers. If the distributions were normal then a maximum likelihood test could be applied to demonstrate mixing (McManus, 1983a). However this is not the case. A bimodal distribution should show a relative minimum, the number of cases increasing to each side of that point. The theoretical minimum in Fig. 1 is at zero, and cases clearly increase in frequency to its right. If cases also increase in frequency to the left of zero then the distribution is bimodal. The regression of cell frequencies upon *degree* of laterality for cells left of zero (log-linear model assuming Poisson variation) is significant (chi-square = 3.698, d.f. = 1,  $P=0.0545$ , two-tailed), the negative slope (i.e. increasing to the left) confirming the minimum at zero, and hence bimodality.

*Direction of lateralization.* Of the 314 children tested, 11.5 per cent were left-handed, 13.4 per cent in males and 9.6 per cent in females. Left-handers showed some change in prevalence across age groups, 11.7, 13.0, 15.5, and 6.7 per cent in 3-, 4-, 5- and 7-year-olds respectively, although analysis using a general linear model for contingency tables (McCullagh & Nelder, 1983) did not show a significant linear trend upon age

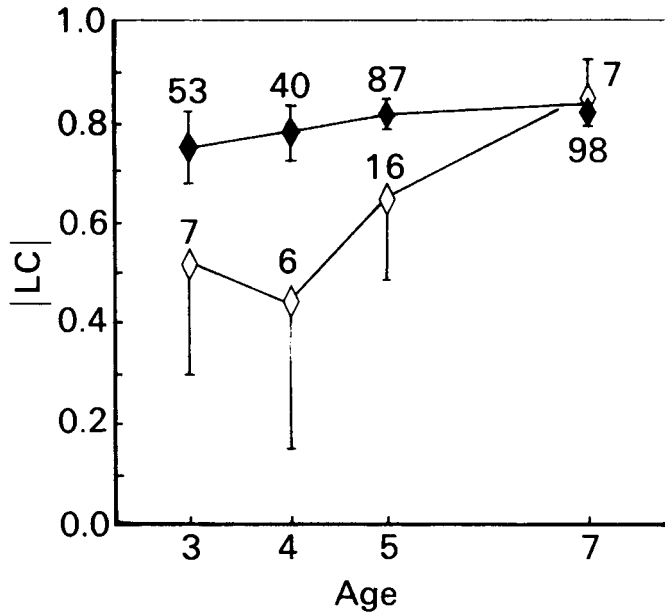


**Figure 1.** Study 1: bimodal distribution of laterality scores calculated from the 10-item performance battery, for all children in Study 1. Bins are centred at values of  $-1(0.1)+1$ , with boundaries of  $-0.95(0.1)0.95$  and  $-0.851(0.1)0.951$ .

(chi-square = 1.73, d.f. = 1, n.s.), or for differences between sexes after taking age into account (chi-square = 1.26, d.f. = 1, n.s.).

*Degree of lateralization.* Three-way ANOVA of *degree* of handedness on *direction* of handedness, age, and sex found significant effects of handedness ( $P < 0.001$ ), age ( $P < 0.001$ ), and their interaction ( $P < 0.05$ ). Unequal sample sizes were accounted for using a classic experimental design, in which unique variance of effects was considered after shared variance had been accounted for (Nie, Hull, Jenkins, Steinbrenner & Bent, 1975). There were no effects of sex ( $P = 0.84$ ), nor interactions

of sex with age or *direction*. Left-handers were less lateralized than right-handers, and younger children less lateralized than older children, both in right-handers (linear trend on age,  $P < 0.001$ ), and in left-handers (linear trend on age,  $P < 0.025$ ), neither group showing evidence of non-linearity. The significant interaction (Fig. 2) shows at age 7 left-handers are as strongly lateralized as right-handers, despite lesser lateralization earlier.



**Figure 2.** Study 1: the mean degree of lateralization  $|LC|$  for children aged 3, 4, 5 and 7 years of age, according to *direction* of lateralization (◇, left-handers; ◆, right-handers), along with 95 per cent confidence limits for means. Numbers alongside points indicate sample sizes.

### Study 2

Study 1 shows that *direction* of handedness is relatively well established by age 3 (or perhaps earlier), whereas degree of lateralization continues to develop until age 7. However there is the suggestion that the prevalence of left *direction* of handedness drops between 5 and 7, although the differences could be due to sampling variation in a transverse study. Study 2 was longitudinal, the 5-year-olds of Study 1 being followed up two years later, to assess change within individuals, avoiding the danger of confusing transverse differences with longitudinal changes.

### Method

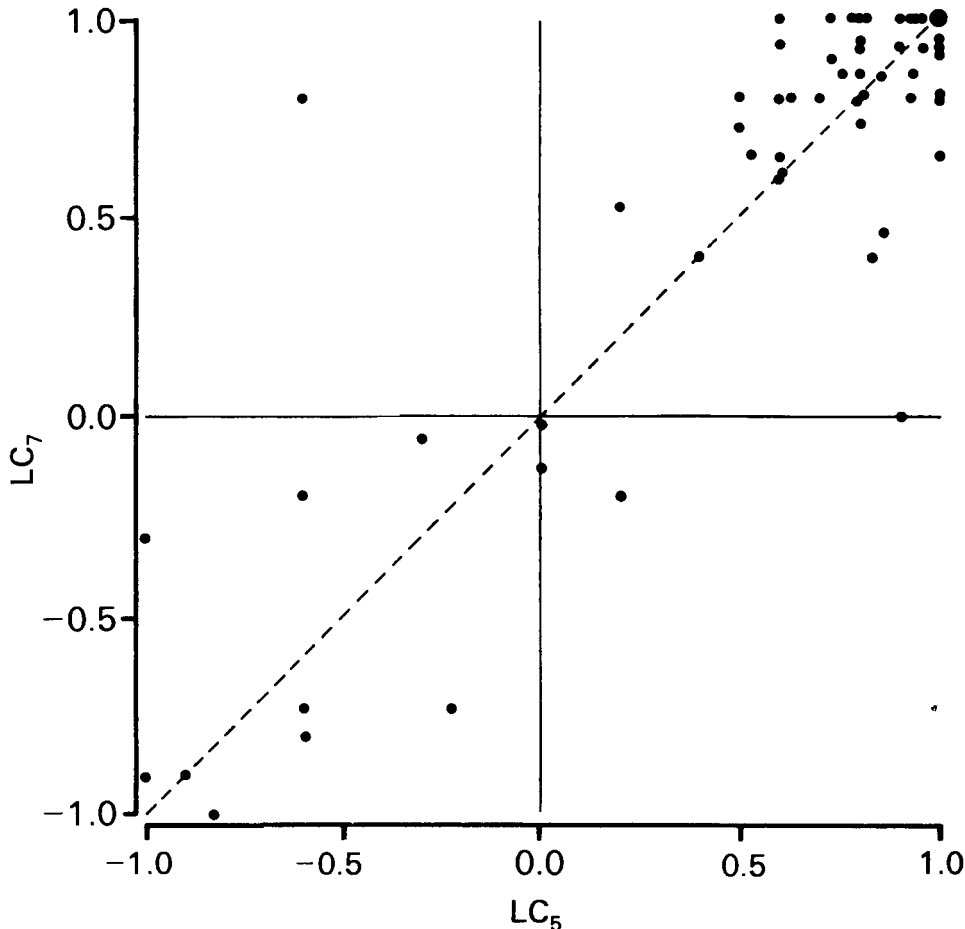
The 5-year-old children in Study 1 were included in the follow-up, the same schools being revisited. Handedness and laterality scores were assessed by G.S. using an identical method to that of Study



## Results

From the total number of children tested, 98 had suitable data in Study 1. At follow-up 66 were identified at the age of 7. This 67 per cent follow-up rate is perhaps the best that can be hoped for, given the high migration rates of this particular inner city area, up to 21 per cent of the population within a single year, with highest rates in young adults who might be the parents of the present children (Hanson & Wilks, 1984). Laterality scores at age 5 of those followed up did not differ significantly from those of drop-outs either in *direction* (16.7 per cent left-handers vs. 12.5 per cent, chi-square = 0.288, d.f. = 1, n.s.), or in *degree* of lateralization (Mann-Whitney test,  $U = 914.5$ , n.s.).

*Direction of lateralization.* Of 66 children, 12 (18.2 per cent) were left-handed at age 5, and 11 (16.7 per cent) were left-handed at age 7; two were left-handed at age 5 and



**Figure 3.** Study 2: laterality scores of children at the age of 5 ( $LC_5$ ; abscissa) and 7 ( $LC_7$ ; ordinate). ●, single subjects; ●, at [1,1] represents eight subjects.

right-handed at age 7, and one child changed in the opposite direction (Fig. 3). McNemar's test, for a change in proportions in related samples, showed no evidence for a change in prevalence of left-handedness (chi-square = 0.33, d.f. = 1, n.s.).

*Degree of lateralization.* Mean *degree* of lateralization in the 66 children was 0.758 (SD = 0.253) at age 5, and 0.787 (SD = 0.241) at age 7, an increase of 0.033 (SD = 0.197). Of the children tested, 32 had increased lateralizations, 18 decreased, and 16 showed no change (McNemar's test, chi-square = 3.92, d.f. = 1,  $P = 0.048$ , two-tailed); since direction of change had been predicted to be the same as in the transverse study, a one-tailed test may be used, giving  $P = 0.024$ . Within right-handers at age 7, 26 had increased lateralization, and 14 decreased (McNemar's test, chi-square = 3.60, d.f. = 1,  $P = 0.029$ , one-tailed), whereas in left-handers six had increased lateralization and four decreased (McNemar's test, not significant). The difference between right- and left-handers is not significant (chi-square = 0.086, d.f. = 1, n.s.).

### Study 3

Studies 1 and 2 suggest *degree* of lateralization increases at least until age 7. Batheja & McManus (1985) suggested that increasing *degree* of lateralization might relate to the asymmetric activities of reading and writing which are learned between 5 and 7. Study 3 examined children up to age 9 to see if lateralization was still progressing, and whether *direction* or *degree* of lateralization related to sex, reading ability or general intelligence.

#### Method

All the 60 children at a small private, co-educational, multi-racial, mixed ability school in North West London were assessed. Measures of reading ability assessed by teachers at the school were available for all but 10 children: the Schonell reading test for 6/7-year-olds, and the Schonell and NFER tests for 8/9-year-olds. Intelligence was assessed by Raven's progressive matrices administered by J.K.; age corrected scores were produced as residuals from the regression of age against logarithm of items correct, the logarithmic transformation removing heteroscedasticity. Reading scores were expressed as age corrected scores relative to norms. Lateralization was assessed as in Study 1. Sixteen children were not born in Western countries, and this factor was assessed separately in analyses.

#### Results

Degree of lateralization increased significantly with age (Fig. 4; Pearson correlation  $r = 0.310$ ,  $P < 0.025$ ). Analysis of the 33 children of age 7 or above showed a non-significant correlation of 0.161, suggesting that *degree* of lateralization either ceases to increase, or increases more slowly, after age 7.

Table 2 shows correlations between laterality, age, sex, non-Western birth, and reading and intelligence scores, in all children, and in children aged over 7 or over. Using multiple regression, only *direction* of lateralization was a significant predictor of *degree* of lateralization ( $t = 2.83$ , d.f. = 44,  $P = 0.007$ , two-tailed), left-handers being less lateralized than right-handers. The effect of age was almost significant on a one-

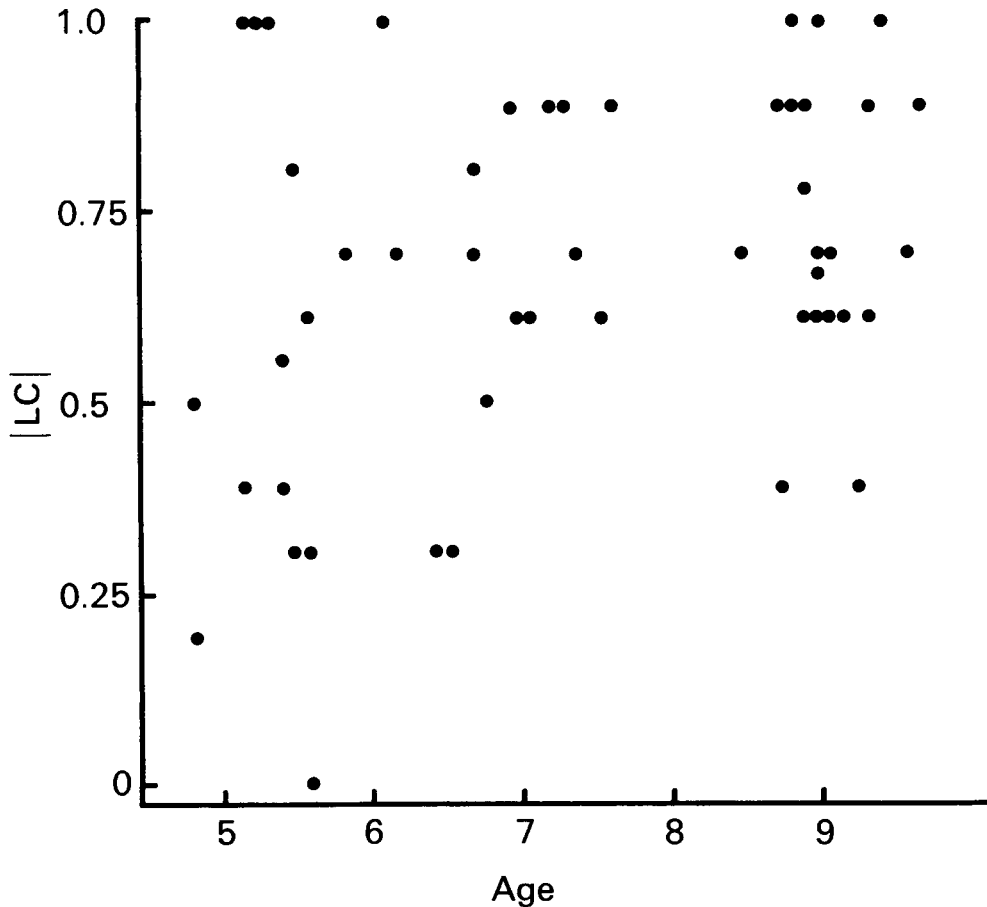


Figure 4. Study 3: degree of handedness of children over the age range 5 to 9 as a function of age.

tailed test ( $t=1.62$ ,  $d.f.=44$ ,  $P=0.054$ ), after taking account of *direction* of handedness. Intelligence, sex and non-Western birth showed no trend towards significance. Considering only children aged over 7, *direction* of lateralization was a significant predictor ( $t=1.82$ ,  $d.f.=27$ ,  $P=0.038$ , one-tailed), with no effect of age, reading ability, or other variables. A similar analysis using *direction* of lateralization as the independent variable found that only *degree* of lateralization was a significant predictor ( $t=2.83$ ,  $P<0.01$ ), with no other variables near to significance. A similar result was found for those children aged over 7.

### Discussion

The results of the three studies can be summarized:

(i) Handedness in children, as assessed by performance, is unidimensional and bimodally distributed (as has also been reported in 5-7-year-olds by Guaraldi,

**Table 2.** Correlations in Study 3 between the six variables of interest, those for all children above the diagonal ( $n=50$ ), and those for children aged 7 or more with reading scores below the diagonal ( $n=33$ )

	Direction of lat'n	Degree of lat'n	Age	Sex	Non- Western	IQ
Direction of lat'n	—	-0.423 ***	-0.164	-0.033	-0.098	-0.025
Degree of lat'n	-0.385 **	—	0.309 **	0.073	0.196 *	0.026
Age	-0.165	0.161	—	0.085	0.253 **	-0.040
Sex	0.241 *	-0.073	-0.025	—	0.199 *	-0.081
Non-Western	-0.021	0.094	-0.057	0.097	—	0.094
IQ	-0.076	-0.038	-0.228 *	-0.001	0.094	—
Reading	-0.246 *	0.169	-0.164	-0.276 *	0.028	0.407 ***

\*  $P < 0.1$ ; \*\*  $P < 0.05$ ; \*\*\*  $P < 0.01$ .

Ruggerini & Bolzani, 1981), and is adequately described by separate measures of *direction* and *degree* of lateralization.

(ii) *Direction* of lateralization is stable at least by age 5, and probably by age 3 or sooner (confirming other studies, e.g. Coren, Porac & Duncan, 1981; Gesell & Ames, 1947; Ingram, 1975; Longoni & Orsini, 1987). Ramsay (1979) has additionally suggested that directional preferences develop between 10 and 15 months, a result compatible with early literature (e.g. Baldwin, 1890; see Harris, 1980, for a review).

(iii) *Degree* of lateralization develops until age 7, when it is stable or changing very slowly. This is similar to *degree* of handedness in monkeys, which correlates with age, up to a threshold beyond which it does not increase, and to ocular dominance in humans which changes in *degree* but not in *direction* from age 44 weeks to adulthood (Coren, 1974).

(iv) *Degree* of lateralization increases more rapidly in left-handers than in right-handers over the age range 3 to 7.

(v) Neither *direction* nor *degree* of lateralization correlates with intelligence or reading ability, a result consistent with findings in prepubescent samples of Porac & Coren (1981).

These findings should be considered together with previous conclusions that the mentally handicapped are less lateralized (Batheja & McManus, 1985) and there is no

familial trend in *degree* of lateralization. It should be emphasized that all these results concern tasks evaluating what Morgan & McManus (1987) call 'handedness/preference' rather than 'handedness/skill'. Preference and skill are often only weakly related, and it is of great interest to know how skill improves during early life. At present one of us (G.S.) is investigating this.

Three classes of explanation of the increasing *degree* of lateralization offer themselves:

- (i) that experience of an asymmetric world induces greater *degree* of lateralization;
- (ii) that increasing *degree* of lateralization is a necessary consequence of increasing encephalization;
- (iii) that increasing *degree* of lateralization is the consequence of evolving and changing cognitive strategies, particularly for dealing with problems of motor control;
- (iv) that *degree of lateralization* is a phenomenon *sui generis*, developing not in response to specific experiences, nor as a consequence of *direction* of brain lateralization, but instead reflecting simple positive feedback whereby hand usage itself makes that hand more preferred for future actions.

The effect of an asymmetric world, explanation (i), is supported by experiments in which mouse 'pawedness' becomes greater when mice are kept in asymmetric worlds (Collins, 1975, 1977). Also adult left-handers are less lateralized than right-handers (e.g. Crovitz & Zener, 1962), precisely for those inventory items for which there is either strong social pressure, or asymmetry in cultural artifacts. Once such items are removed, left-handers and right-handers show equal *degree* of lateralization (McManus, 1979). This suggests a lack of generalization to other lateralized tasks. Neither does explanation (i) explain the present results, where firstly there is no correlation between *degree* of lateralization and proficiency at lateralized tasks such as reading, and secondly in the age range 3 to 7 left-handers show a greater increase in lateralization, despite being exposed to a world lateralized in an opposite direction to their functional adaptation. The specific hypothesis that learning to write increases *degree* of lateralization can only be tested by a panel study assessing writing and lateralization at several ages; such a study would be of great interest. Finally, it is not obvious that the most lateralized tasks (in terms of discrimination coefficients, rather than numbers of M-B responses which merely reflect specific task requirements) are those which show most lateralization in social demands or in inherent asymmetry (in contrast to the results in adults, McManus, 1979). It is not obvious why toothbrush use is more lateralized than nose-blowing, or bead-threading than ball-throwing, in social or cultural constraints. Such mysteries would be partly resolved if the skill demands of the tasks were known in addition to lateral preferences for such skills.

Increasing encephalization, explanation (ii), is harder to test, arguing that increasing brain size necessarily entails greater brain lateralization, in the sense that individual brains would show increasing lateralization, although without population dominance necessarily being apparent. The theory would explain the phylogeny of lateralization, primates showing greater *degree* of individual lateralization, and also explains the lesser *degree* of lateralization of the mentally handicapped, some of whom

will be relatively microcephalic. It is also consistent with findings in mice in which animals with greater *degree* of behavioural lateralization also have larger brains (but do not have anatomically more asymmetric brains). Of course the absence of a correlation between *degree* of lateralization and human intelligence (in the normal range) is not an embarrassment, since in man brain size and intelligence do not correlate.

Explanation (iii) is not easy to test. Cognition, motor control and *degree* of lateralization certainly mature together, but that does not imply a causal relationship. Probably until the relationship between cognition and motor control is better understood then the model cannot be adequately tested. An implicit assumption is that lateralization is a high level, probably cortical, activity. Some evidence (e.g. Glick & Shapiro, 1984) suggests though that preference asymmetries result from primitive, brain-stem asymmetries, which are unlikely to be influenced by cognitive processes.

Explanation (iv), of a phenomenon *sui generis*, is a baseline for comparing other theories. The theory says that the world needs to be acted upon unimanually, and initially both hands might be functionally equivalent. Each time that a particular hand is used it becomes more likely to be used in the future; a self-reinforcing loop is created and increasing *degree* of lateralization is the consequence. This is not a learning theory in the sense that stimulus demands reinforce usage of one hand over the other. Rather the individual chooses the hand used before, perhaps for reasons of increasing task efficiency, implying a monitoring of proficiency. However, the hand might be chosen independently of efficiency; Peters (1983, p. 146) has argued that such effects can eventually produce increasingly large asymmetries. Explanation (iv) predicts no correlation between *degree* of lateralization and measures of task demand asymmetry or intellectual ability, and can thus explain decreased lateralization in the mentally handicapped, by postulating deficiencies at the relatively low level required to render usage of one hand more likely when it has been used previously. At its simplest the theory argues that *degree* of handedness is entirely a question of handedness/preference rather than handedness/skill.

In summary, *degree* of handedness increases as children grow older, but this is not related to the demands of asymmetric tasks or of an asymmetric world. Possible explanations might be that it is the increasing cerebral mass *per se* which necessitates an increasing *degree* of lateralization, or alternatively that lateralization might be a functional phenomenon *sui generis*. Whilst the latter might not be regarded as an 'interesting' explanation, it may nonetheless be an adequate description of the phenomenon, and would readily account for the absence of evidence in man for genetic control over *degree* of lateralization.

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## References

- Annett, M. (1972). The distribution of manual asymmetry. *British Journal of Psychology*, **63**, 343–358.
- Annett, M. (1985a). *Left, Right, Hand and Brain: The Right Shift Theory*. London: Erlbaum.
- Annett, M. (1985b). Which theory fails? A reply to McManus. *British Journal of Psychology*, **76**, 17–29.
- Annett, M. & Kilshaw, D. (1985). Right and left-hand skill. II: Estimating the parameters of the distribution of L-R differences in males and females. *British Journal of Psychology*, **74**, 269–283.
- Baldwin, J. M. (1908). Origin of right or left handedness. *Science*, **16**, 247–248.
- Batheja, M. & McManus, I. C. (1985). Handedness in the mentally handicapped. *Developmental Medicine and Child Neurology*, **27**, 63–68.
- Beaton, A. (1985). *Left Side, Right Side: A Review of Laterality Research*. London: Batsford.
- Boklage, C. E. (1981). On the distribution of non-right-handedness among twins and their families. *Acta Genetica Medica et Gemellologica*, **30**, 167–187.
- Bradshaw, J. (1980). Right-hemisphere language: Familial and non-familial sinistrals, cognitive deficits and writing hand position in sinistrals, and concrete–abstract, imageable–nonimageable dimensions in word recognition. A review of inter-related issues. *Brain and Language*, **11**, 87–98.
- Brooker, R. J., Lehman, R. A. W., Heinbuch, R. C. & Kidd, K. K. (1981). Hand usage in a colony of Bonnett monkeys, *Macaca radiata*. *Behavior Genetics*, **11**, 49–56.
- Bryden, M. P. (1977). Measuring handedness with questionnaires. *Neuropsychologia*, **15**, 617–624.
- Bryden, M. P. (1982). *Laterality: Functional Asymmetry in the Intact Brain*. New York: Academic Press.
- Carter-Saltzman, L. (1980). Biological and socio-cultural effects on handedness: Comparison between biological and adoptive families. *Science*, **209**, 1263–1265.
- Cattell, R. B. (1966). The scree test for the number of factors. *Multivariate Behavioural Research*, **1**, 245–276.
- Collins, R. L. (1970). The sound of one paw clapping: An enquiry into the origins of left-handedness. In G. Lindzey & D. D. Thiessen (Eds), *Contributions of the Behaviour-Genetic Analysis: The Mouse as a Prototype*, pp. 115–136. New York: Appleton-Century-Crofts.
- Collins, R. L. (1975). When left-handed mice live in right-handed worlds. *Science*, **187**, 181–184.
- Collins, R. L. (1977). Towards an admissible genetic model for the inheritance of the degree and direction of asymmetry. In S. Harnad, R. W. Doty, L. Goldstein, J. Jaynes & G. Krauthamer (Eds), *Lateralisation in the Nervous System*, pp. 137–150. New York: Academic Press.
- Collins, R. L. (1981). A demonstration of an inheritance of the direction of asymmetry that is consistent with the notion that genetic alleles are left-right indifferent. *Behaviour Genetics*, **11**, 596a.
- Collins, R. L. (1985). On the inheritance of the direction and degree of asymmetry. In S. D. Glick (Ed.), *Cerebral Lateralisation in Sub-Human Species*, pp. 41–70. New York: Academic Press.
- Collins, R. L., Carlson, G. A. & Nadeau, J. H. (1985). Differential distribution of H-2 haplotypes in lines of mice selectively bred for degree of lateralisation. Society for Neuroscience, 15th Annual Meeting, Dallas, Texas.
- Coren, S. (1974). Development of ocular dominance. *Developmental Psychology*, **10**, 304.
- Coren, S., Porac, C. & Duncan, P. (1981). Lateral preference behaviours—pre-school children and young adults. *Child Development*, **52**, 443–450.
- Crovitz, H. F. & Zener, K. (1962). A group test for assessing hand and eye-dominance. *American Journal of Psychology*, **75**, 271–276.
- Curtiss, S. (1985). The development of human cerebral lateralisation. In D. F. Benson & E. Zaidel, *The Dual Brain: Hemispheric Specialisation in Humans*, pp. 97–116. New York: Guilford Press.
- Darwin, C. (1877). A biographical sketch of an infant. *Mind*, **2**, 285–294.
- Dee, H. L. (1971). Auditory asymmetry and strength of manual preference. *Cortex*, **7**, 236–245.
- Fennell, E. B., Satz, P. & Morris, R. (1983). The development of handedness and dichotic ear listening asymmetries in relation to school achievement: A longitudinal study. *Journal of Experimental Child Psychology*, **35**, 248–262.
- Fraser, C. (undated). NOHARM II: A Fortran program for fitting unidimensional and multidimensional normal ogive models of latent trait theory. Armidale, NSW, Australia: Centre for Behavioural Studies.
- Gesell, A. & Ames, L. B. (1947). The development of handedness. *Journal of Genetic Psychology*, **70**, 155–175.

- Glick, S. D. & Shapiro, R. M. (1984). Functional and neurochemical asymmetries. In N. Geschwind & A. M. Galaburda (Eds), *Cerebral Dominance: The Biological Foundations*, pp. 147-166. Cambridge, MA: Harvard University Press.
- Guaraldi, G. P., Rugggerini, C. & Bolzani, R. (1981). La preferenza manuale in età scolare: Rilievi epidemiologici ed analisi di fattori congeniti ed acquisiti. *Neuropsichiatria infantile*, **235-236**, 179-197.
- Hanson, F. & Wilks, M. (1984). Mobile patients in an inner London practice. *British Medical Journal*, **288**, 1579-1582.
- Hardyck, C., Goldman, R. & Petrinovich, L. (1975). Handedness and sex, race and age. *Human Biology*, **47**, 369-375.
- Hardyck, C. & Petrinovich, L. F. (1977). Left-handedness. *Psychological Bulletin*, **84**, 385-404.
- Harris, L. J. (1980). Left-handedness: Early theories, facts and fancies. In J. Herron (Ed.), *Neuropsychology of Left-handedness*, pp. 3-78. New York: Academic Press.
- Hildreth, G. (1949). The development and training of hand dominance. *Journal of Genetic Psychology*, **70**, 197-275.
- Ingram, D. (1975). Motor asymmetries in young children. *Neuropsychologia*, **13**, 95-102.
- Leiber, L. & Axelrod, S. (1981). Intra-familial learning is only a minor factor in manifest handedness. *Neuropsychologia*, **19**, 273-288.
- Levy, J. (1976). A review of evidence for a genetic component in handedness. *Behaviour Genetics*, **6**, 429-453.
- Longoni, A. M. & Orsini, L. (1987). Lateral preferences in preschool children. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, in press.
- Lord, F. M. (1952). A theory of test scores. *Psychometric Monographs*, No. 7.
- McCullagh, P. & Nelder, J. A. (1983). *Generalised Linear Models*. London: Chapman & Hall.
- McDonald, R. (1982). Linear versus non-linear models in item-response theory. *Applied Psychological Measurement*, **6**, 379-396.
- McManus, I. C. (1979). Determinants of laterality in man. Unpublished PhD thesis, University of Cambridge.
- McManus, I. C. (1981). Handedness and birth stress. *Psychological Medicine*, **11**, 485-496.
- McManus, I. C. (1982). The distribution of skull asymmetry in man. *Annals of Human Biology*, **9**, 167-170.
- McManus, I. C. (1983a). The interpretation of laterality. *Cortex*, **19**, 187-214.
- McManus, I. C. (1983b). Pathological left-handedness: Does it exist? *Journal of Communication Disorders*, **16**, 315-344.
- McManus, I. C. (1984). The genetics of handedness in relation to language disorder. In F. C. Rose (Ed.), *Advances in Neurology*, vol. 42, *Progress in Aphasiology*, pp. 125-138. New York: Raven Press.
- McManus, I. C. (1985a). Right- and left-hand skill: Failure of the right shift model. *British Journal of Psychology*, **76**, 1-16.
- McManus, I. C. (1985b). On testing the right shift theory: A reply to Annett. *British Journal of Psychology*, **76**, 31-34.
- McManus, I. C. (1985c). Handedness, language dominance, and aphasia: a genetic model. *Psychological Medicine*, Monograph Supplement, Number 8.
- Morgan, M. J. & McManus, I. C. (1987). The relationship between brainedness and handedness. In F. C. Rose, R. Whurr & M. Wyke (Eds). London: Whurr Books (in press).
- Nie, N. H., Hull, C. H., Jenkins, J. G., Steinbrenner, K. & Bent, D. H. (1975). *SPSS: Statistical Package for the Social Sciences*, 2nd ed. New York: McGraw-Hill.
- Oldfield, R. C. (1969). Handedness in musicians. *British Journal of Psychology*, **60**, 91-99.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, **9**, 97-113.
- Peters, M. (1983). Differentiation and lateral specialisation in motor development. In G. Young, S. J. Segalowitz, C. M. Corter & S. E. Trehub (Eds), *Manual Specialisation and the Developing Brain*, pp. 141-159. New York: Academic Press.
- Porac, C. & Coren, S. (1981). *Lateral Preferences and Human Behaviour*. New York: Springer-Verlag.
- Ramsay, D. S. (1979). Manual preference for tapping in infants. *Developmental Psychology*, **15**, 437-442.
- Ramsay, D. S. (1985). Fluctuations in unimanual hand preference in infants following the onset of duplicated syllable babbling. *Developmental Psychology*, **21**, 318-324.



- Ratcliff, G., Dila, C., Taylor, L. & Milner, B. (1980). The morphological asymmetry of the hemispheres and cerebral dominance for speech: A possible relationship. *Brain and Language*, **11**, 87-89.
- Roszkowski, M. J., Snelbecker, G. E. & Sacks, R. (1980). Is age correlated with right-handedness? *Perceptual and Motor Skills*, **51**, 862.
- Sinclair, C. (1971). Dominance patterns of young children: A follow-up study. *Perceptual and Motor Skills*, **32**, 142.
- Tan, L. E. (1985). Laterality and motor skills in four-year-olds. *Child Development*, **56**, 119-124.
- Ward, R. & Collins, R. L. (1985). Brain size and shape in strongly and weakly lateralised mice. *Brain Research*, **328**, 243-249.
- Ward, R. L., Giguere, L. & St.-Yves, M. (1986). Some behavioural differences between strongly and weakly lateralized mice. *Behaviour Genetics*, in press.
- Young, G., Segalowitz, S. J., Corter, C. M. & Trehub, S. E. (1983) (Eds), *Manual Specialisation and the Developing Brain*. New York: Academic Press.

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