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Brain and Cognition 52 (2003) 390–398

Brain and Cognition

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Hand laterality and cognitive ability: A multiple regression approach

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Accepted 1 June 2003

Abstract

Several different associations between hand laterality and cognitive ability have been proposed. Studies reporting different conclusions vary in their procedures for defining laterality, and several of them rely on measures which are statistically problematic. Previous methods for measuring relative hand skill have not satisfactorily separated the overall level of hand skill, which is a known correlate of cognitive ability, from the asymmetry of its distribution. This paper uses a multiple regression paradigm that separates these two components. Support is found for Leask and Crow's [Trends in Cognitive Sciences, 5 (2001) 513] proposal that average cognitive ability increases monotonically with increasing strength of laterality, regardless of its direction. The small average advantage to dextrals stems from them being more strongly lateralised than sinistrals. The paucity of strong dextrals amongst the very gifted is due to a smaller variance in cognitive ability in this group.

Keywords: Handedness; Intelligence; IQ; Lateralization

1. Introduction

> The association between particular patterns of hand preference and mental ability is frankly obscure—Newcombe et al. (1975, 236)

There have many studies investigating the possible relationship between hand laterality and cognitive abilities. Almost every conceivable relationship has been supported in the literature. Traditional speculations generally posited a disadvantage to sinistrality. One large-scale population study does indeed show a mean advantage to right-handers over non-right-handers in General Ability, an IQ-like score (McManus & Mascie-Taylor, 1983). However, the advantage is extremely slight. Other studies failed to find any such association (Hardyck, Petronovich, & Goldman, 1976; Newcombe et al., 1975). Hardyck, Petronovich and Goldman concluded that 'of the intellectual and cognitive tasks assessed to date... there is no difference in... performance that can be attributed to any deficit linked to handedness' (p. 277). However, McManus, Shergill, and Bryden (1993) suggest that on one IQ test, the Hardyck sample does show a minute but highly significant mean dextral advantage, bringing the results at least partly into conformity with McManus and Mascie-Taylor (1983).

Benbow (1986) studied a large group of students who were extremely high scoring relative to their peers in terms of either mathematical or verbal ability, and found what she described as an excess of mixed- and left-handedness. Closer examination of the data shows that there is in fact a rarity of strong dextrals. Every other group, including weak or average dextrals, is over-represented in the gifted sample, whilst extreme dextrals are scarce (Benbow, 1986, Table 2). Noroozian, Lotfi, Gassemzadeh, Emami, and Mehrabi (2002), using a large sample, found that left-hand writers achieved slightly more highly on Iranian university entrance exams than right-hand writers, though the difference was significant only in the subject of Art. These findings are compatible with the view that unusually high abilities in specific domains are often associated with non-right handedness, a case that has also been demonstrated for music (Aggleton, Kentridge, & Good, 1994; Hassler & Gupta, 1993).

On the other hand, an excess of non-right handedness is also associated with unusually low intellectual

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doi:10.1016/S0278-2626(03)00187-8

achievement (Annett & Turner, 1974; Bishop, 1984). Thus at the very least there is considerable heterogeneity amongst sinistrals, heterogeneity that is captured by the distinction between pathological and non-pathological sinistrality (Harris & Carlson, 1988).

Annett and Manning (1989) find that IQ scores amongst dextrals are highest amongst those whose hand skill is only weakly asymmetric to the right, and are sharply reduced amongst strong dextrals. They interpret this result in the light of Annett's balanced polymorphism-heterozygote advantage model (Annett, 1985), which predicts deficits at both extreme ends of the laterality continuum. Crow, Crow, Done, and Leask (1998) use the large data set provided by one of Britain's national child cohort studies. They find some evidence for the strong-dextral disadvantage, but also stronger evidence for ability deficits close to the point where the two hands are equally skilled. This they interpret in the light of their model of human cognitive evolution, in which the development of lateralization is the key characteristic which enables language and other aspects of human-specific cognition. However, Mayringer and Wimmer (2002), in an attempt to replicate the Crow et al. findings, found no evidence for the deficit at the point of equal hand skill.

Leask and Crow (2001) reanalysed the data set used by Crow et al. (1998). They now argued that there was no evidence of a fall-off in General Ability or any of its components at the extremes of the laterality continuum. They continued to argue for deficits at the point of equal hand skill, and suggested that ability scores rise monotically as one moves away from this point, in either direction. These very interesting suggestions were unfortunately not backed up with any inferential statistics. In their paper, the reader is invited to draw conclusions from 3-D graphs, but no estimates of statistical significance or effect size are given.

The purpose of this paper is to clarify the relationship between hand laterality and cognitive abilities. The first part is a methodological review of the studies listed above. Many of the discrepancies may result from the use of different measures of hand laterality. More particularly, I show that the laterality indices used by Crow et al. (1998), and perhaps by Annett and Manning (1989), are potentially invalid, and apt to produce odd effects at the extremes in virtue of their undesirable statistical properties. Where data are adduced to support the argumentation, they are from the National Child Development Study (NCDS). This is the large data set which was also used by McManus and Mascie-Taylor (1983), Crow et al. (1998), and Leask and Crow (2001), though the version of the data set used here is slightly different (see Appendix A for a description). The second part of the paper is a multiple regression analysis of the NCDS ability and laterality data. The purposes of this new analysis are: (1) to look for effects at the extremes of laterality and at the point of equal hand skill using a more valid index of laterality; (2) to provide statistical tests of the relationships suggested by Leask and Crow (2001); and (3) to relate the claimed differences between sinistrals and dextrals in this cohort to the Leask and Crow model. The result is a fairly clear picture of the relationship between laterality and cognitive ability.

2. Methodological review

It is important to distinguish between three different factors that can all vary among individuals. One is *cerebral lateralization for speech*, the second is *hand preference* for a given activity or set of activities, and the third is *relative hand skill*. The three are inter-related but not identical. For example, in the NCDS data, the overwhelming majority of individuals (97%) are more skilled on the box-ticking task with the hand that they prefer for writing than with the other hand. However, there is wide variation in the degree of skill differential. Moreover, 17% of those who are more skilled with the left hand nonetheless prefer the right hand for writing. This is presumably a consequence of social pressure, since the converse does not hold, with less than 1% of those who are more skilled with the right hand preferring the left to write with. Hand preference is also related to cerebral lateralization for speech. Speech is lateralised to the left in 96% of right-hand writers, but less than 70% of left-hand writers (Annett, 1985, Table 3.2).

Studies of cognitive abilities and hand laterality vary in whether they measure hand preference or relative hand skill. Within those that measure hand preference, there is variation in the number of items which are tested (for example, just writing, writing plus wielding a hammer, kicking a ball, using a racket, etc.). Hand preference questions generally yield trichotomous classifications of right, left, and mixed preference. If the question is just about writing, then the number in the mixed category will be vanishingly small, and that in the left category less than 10%. As other activities are included, the proportion of the population showing some evidence of mixed preference rises steadily. When the number of items becomes large, the number of 'right-hand' responses as a proportion of the number of items gives a quasi-continuous laterality index (McManus et al., 1993). Maximal dextrality on an index like this is very rare (McManus et al., 1993, Fig. 2). Thus, the portion of the population that is termed non-right handed will depend on the hand preference questionnaire used, and the cut-off point if the measure is quasi-continuous.

Of the papers cited above, most used hand preferences to measure hand laterality (Annett & Turner, 1974; Benbow, 1986; Hardyck et al., 1976; McManus & Mascie-Taylor, 1983; Newcombe et al., 1975; Noroozian et al., 2002). Annett and Turner (1974), McManus and Mascie-Taylor (1983), Hardyck et al. (1976), and Noroozian et al. (2002) basically used writing hand (though in some cases checking this against eye preference and use of scissors). This gives over 90% of the population in the dextral group. Newcombe et al. (1975) used a seven-item preference questionnaire and only those participants who answered 'right' to all seven were classified as dextral, a criterion met by only 74% of participants. Benbow (1986) used a 10-item preferences questionnaire, which made only 41.6% of the control group right-handed, if right-handed is taken to mean answering all 10 items with 'right'. This does appear to be an appropriate interpretation, since the difference between the gifted and control groups is completely accounted for by the scarcity amongst the former of those scoring all 10 items to the right (Benbow, 1986, Table 2). Thus, the different conclusions reached by these studies could follow from definitions of right-handedness which include different parts of the population.

The five remaining studies did not use hand preferences but relative hand skill. This is surely desirable. Activities such as writing and using a hammer are culturally taught, and so their expression of inherent nervous system laterality will be mediated by other factors. Moreover, hand preference indices are not truly continuous, and do not discriminate between someone who does all major tasks with the right hand but is skilled with the left hand too from someone who is genuinely weak on the left hand. However, correctly characterising asymmetry of hand skill is not entirely straightforward.

Bishop (1984), Annett and Manning (1989), Crow et al. (1998), Leask and Crow (2001), and Mayringer and Wimmer (2002) all use measures which compare the performance of one hand against the other on a manual task. For Annett and Manning (1989) and Mayringer and Wimmer (2002), this is a score on the peg-moving task (Annett, 1970). For the studies which use the NCDS data, it is the number of small boxes ticked with a pen in a minute. Part of the difference in findings could be attributable to the differences between the tasks. The box-ticking task produces a clearer discrimination between the hands than the peg-moving (Mayringer & Wimmer, 2002, p. 704). However, since the box-ticking task uses a pen, it is possible that it is affected by writing experience rather than being a pure measure of intrinsic manual laterality. This possibility has implications for the interpretation of the NCDS results, to which we return in Section 4. However, many of the differences in conclusions emerge from studies using the same task, so we suggest that the source of much of the confusion may be in the statistical procedures for measuring laterality rather than the task used.

As a measure of laterality, Annett and Manning (1989) and Mayringer and Wimmer (2002) consider the differences between the scores of the two hands (i.e., $R-L$) (the scores are standardised by Annett and Manning but not by Mayringer and Wimmer). Crow et al. (1998) consider the differences between the two hands as a proportion of overall performance on the task (i.e., $(R-L)/(R+L)$). In what follows, I examine possible problems with these characterisations of laterality.

The first point to note is that the overall level of hand skill $(R+L)$ is correlated with IQ. In the NCDS data (see Appendix A), this correlation is 0.18 for boys ($df = 4208$, $p < .001$) and 0.17 for girls ($df = 4316$, $p < .001$). This correlation should come as no surprise when we consider what the general factor of IQ is: a statistical extraction from the manifold of positive correlations observed when the same individuals do many different tasks (Mackintosh, 1998). These tasks include not just activities that are clearly 'cognitive' or 'academic,' but many spatial manipulations, and measures of reaction time (Deary, Der, & Ford, 2001). Given that both the box-ticking and peg-moving paradigms are spatial tasks with a speed component, some loading of overall performance on the general factor of IQ is inevitable.

It is thus essential that any measure of relative hand skill be completely independent of overall level of task performance. If it is not, then some kind of artifactual correlation with IQ is more or less assured. Crow et al.'s approach is to consider the ratio $(R-L)/(R+L)(*100)$, which they call Relhand (i.e., *rel*ative *hand* skill). Using this measure, they show that GA scores are low where Relhand is close to zero and low again where Relhand is very large. In the middle part of its range, Relhand is weakly positively associated with ability scores. The finding is illustrated by Fig. 1, which shows an equivalent analysis for our version of the NCDS dataset. The cohort members are ranked into 5% bins of increasing Relhand scores. Left-handers are in bins one and two. The point of equal hand skill is in bin 3, then further bins represent increasing magnitudes of dextrality.

Crow et al. interpret the pattern in Fig. 1 as an indication of cognitive deficits close to the point of equal hand skill, and also as giving some support to Annett's idea of deficits at the extreme of dextrality. However, the evidential basis of this conclusion is open to question. Relhand is a ratio, and ratios are extremely problematic from a statistical point of view, not least because they change in a non-linear manner as their components vary. Relhand is no exception. In our analysis, it has massive skew and kurtosis (for boys: ratio of skew to its standard error 23.78; ratio of kurtosis to its standard error 19.74; for girls: ratio of skew to its standard error 24.28; ratio of kurtosis to its standard error 50.69). Neither the skewness nor the kurtosis can be eliminated by either logarithmic or square-root transformation.

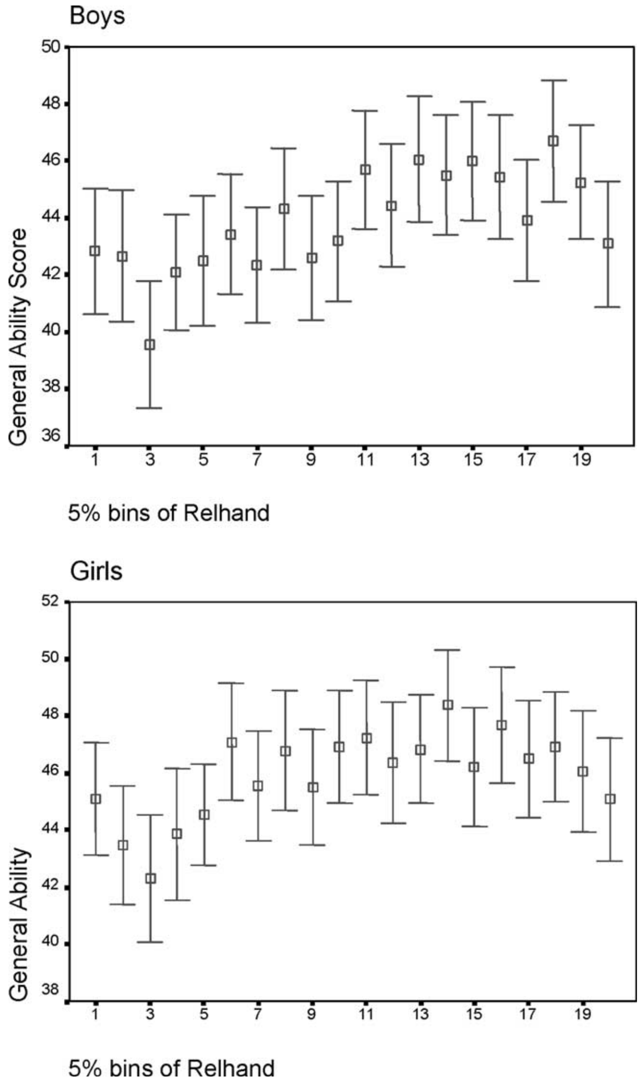

Fig. 1. Mean General Ability scores (with 95% confidence intervals) for individuals in the 5% bins of the distribution of Relhand ((R − L)/(R + L)*100). Groups 1 and 2 contain left-handers and group 3 contains the point of equal hand skill.

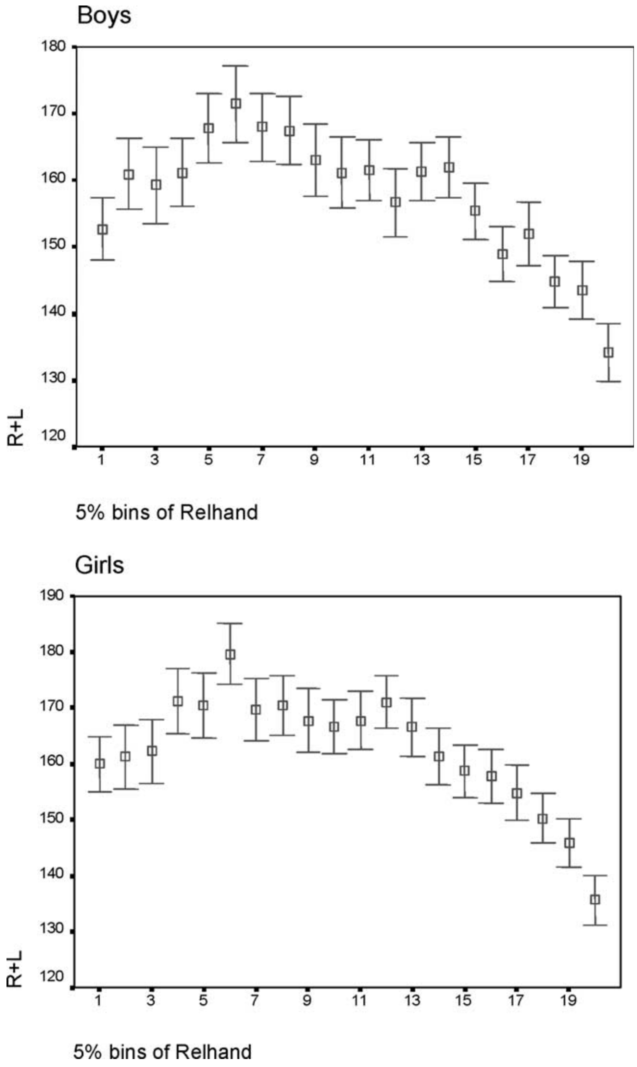

Fig. 2. Means of total number of boxes ticked (R + L) for individuals in the different 5% bins of Relhand ((R − L)/(R + L)*100). Groups 1 and 2 contain left-handers and group 3 contains the point of equal hand skill.

Most importantly, Relhand is not independent of the total level of hand skill.

Fig. 2 shows a similar plot to Fig. 1, but this time showing the total number of boxes ticked (R + L) instead of GA score. Overall ticking skill is greater in weak dextrals (e.g., groups 6–9) than those near the point of equal hand skill. It is easy to see statistically why this must be the case. Those near the point of equal hand skill have a Relhand score close to or equal to zero. For the ratio (R − L)/(R + L) to be close to zero, R has to be exactly equal to L, or R and L must both be quite large and similar in value. The former of these possibilities is more likely the smaller R and L are. Consider drawing two numbers from a hat. The probability of the numbers being exactly the same is not independent of their magnitude. If they are below 15, then the probability of their being identical is higher than if they are both below 30. This is true even if the variances are equal, since in the normal distribution, the probability of a variable assuming a given value is never zero, and anyway the data here are not normal.

A stronger effect in Fig. 2 is the lower level of overall ticking skill at the extreme of dextrality. This too has a statistical explanation. The total skill R + L is the *denominator* of Relhand; hence as it increases, even if the relationship with laterality is truly null, Relhand will decrease. Conversely, the prime way for Relhand to be very large is for R and L both to be small. Thus the tail-off in R + L with increasing values of Relhand is to be expected. Given that R + L is a known correlate of General Ability, for reasons that have nothing to do with lateralization, then its statistical non-independence of Relhand invalidates Relhand as a measure. Changes in cognitive abilities either at the extremes of Relhand or close to zero could be statistical artefacts.

We now turn to Annett and Manning (1989), whose methods are picked up by Mayringer and Wimmer (2002). To recall, Annett and Manning provide evidence of decreasing ability with increasingly strong dextrality. The measure of relative hand skill used is R – L, the simple difference between left- and right-hand performance. However, Annett and Manning correct the R and L scores for age norms of performance, and present them rather like IQs, standardised values with a benchmark mean of 100 and a standard deviation of 15. A close look at Annett and Manning's data (e.g., Annett & Manning, 1989, Table 2) shows that their measure R – L is far from independent of R + L. This is because their 'strong dextrals' are good with the right hand and weak with the left, whereas their 'weak dextrals' are good with both. Thus the average of the two hands is higher in the weak dextrals than the strong, and given we know that overall hand skill is related to IQ, Annett and Manning's weak dextral advantage follows trivially.

To be fair to Annett and Manning, their model is based on the idea that increasing dextrality is achieved developmentally by the suppression of the non-dominant hemisphere, not the enhancement of the dominant. From this, it should be expected that R + L and R – L will be (inversely) correlated, and indeed, Annett and Manning see it as compatible with their model. At the very least, though, it requires a restatement of their conclusions, since it is not extreme dextrality per se, but low overall hand skill, which is associated with IQ deficits. It just happens that low overall hand skill manifests itself particularly in the weaker hand (as has been observed elsewhere, Bishop, 1984), thus producing what looks like an effect of lateralization.

More than this, the fact that Annett and Manning find no difference between very high and very low IQ groups in right-hand performance on the peg moving task (1989, Table 2) is worrying. There should be a difference, since all these tasks load on the general factor of intelligence. In the NCDS data, both R and L performance load on the IQ score, General Ability. What is more, R and L are highly positively correlated with each other (Table 1). The absence of these effects in the Annett and Manning (1989) data suggests that there could be a ceiling effect operating on the stronger hand. If the subjects are doing the peg-moving task nearly as fast as it is physically possible to do it with the right hand, then the effect of increasing general hand skill will be to narrow the difference between the hands. Once again, what is actually an effect of general hand skill will appear to be an effect of lateralization.

Table 1
Correlations between right-hand score, left-hand score, total score, and General Ability in the NCDS sample

	GA	R + L	L
Boys ($n = 4209$)			
R	0.20	0.89	0.54
L	0.12	0.87	
R + L	0.18		
Girls ($n = 4316$)			
R	0.19	0.91	0.54
L	0.12	0.88	
R + L	0.17		

All correlations significant at $p < .001$.

These possibilities are impossible to test without Annett and Manning's raw data. They do suggest, however, that we should be careful of concluding that there are deficits in cognitive abilities at the extremes of dextrality unless clearer analyses are adduced. Much the same can be said for Mayringer and Wimmer (2002). These investigators used, as a measure of lateralisation, the difference between the two hands in mean time to perform the peg-moving task. This difference will not be independent of overall hand skill, for the reasons discussed above, but since Mayringer and Wimmer do not standardise their scores, the bias is the opposite way (that is, their R and L values are not scores, where higher is better, but timings, where lower is better). Thus the discrepancy between their findings and both Annett and Manning's (1989) and Crow et al.'s (1998) may follow from their different statistical procedures.

To summarise this section, studies using hand preference as the index of laterality have found either no difference or a small left-hand disadvantage in average IQ, but suggested a paucity of strong dextrals amongst the extremely able and the relatively impaired. Three of the main studies using continuous relative hand skill measures are inconclusive for statistical reasons. The third (Leask & Crow, 2001) is suggestive but lacks quantification of effect size and significance. In the next section, I use the NCDS data to provide a new index of hand skill laterality, and to test for the various hypothesised effects of hand laterality on cognitive ability.

3. A multiple regression approach

The desiderata for an index of hand laterality are that it should ideally measure relative hand skill rather than hand preference, that it should be a continuous variable, that it should be in principle independent of the level of hand skill, and that it should not be a ratio.

Multiple regression has the potential to tease out the confounding effects of overall hand skill. Regressing General Ability score on total number of boxes ticked (R + L) gives a positive relationship, as discussed above. The question is thus whether addition of the difference between the stronger and weaker hand (R – L) as a further independent variable improves the power of the model. If it does not, then the effect is merely one between overall hand skill and General Ability. If it does, then there is an independent effect of laterality per se.

Table 2 gives the stepwise multiple regression equations for this analysis broken down into boys and girls, and right versus left hand stronger. Both (R + L) and (R – L) are significant predictors of GA in all cases except the left-advantage girls, for whom only (R + L) is significant. The effects are of modest size, with (R + L) accounting for about 3% of the variation, and (R – L) about another 1% in the cases where it is significant. None of the equations in Table 2 differs significantly from any other (the coefficients all fall within each other's 95% confidence intervals), except that for the left-hand advantaged boys, the direction of the effect of (R – L) is reversed. This is to be expected since for left-handers (R – L) is negative and decreases with increasingly strong laterality, the opposite of the situation for right-handers.

The fact that the equations do not differ significantly mean that for present purposes, we can pool boys and girls. We can also pool left and right advantage groups by taking the modulus of (R – L) rather than its signed value. This pooling gives the master equation at the bottom of Table 2. Overall, (R – L) accounted for 1.1% of the variance in GA once the effect of (R + L) had been taken into consideration. The direction is positive, meaning that as laterality increases in either direction away from the centre, average GA weakly increases. There is no difference in the slope of the relationship according to whether the laterality is toward the left or the right, or by sex. The r^2 values are not increased by considering either just the verbal or just the non-verbal component of GA.

The relationship is graphically illustrated by Fig. 3. With such a weak effect, the relationship is hard to see on a conventional scatterplot. Instead, the absolute value of (R – L) has been divided up into 5% bins. The variable on the y-axis is the GA score, adjusted for the known effect of R + L. The relationship clearly shows that people become more lateralised (whichever direction), their mean GA scores are somewhat increased.

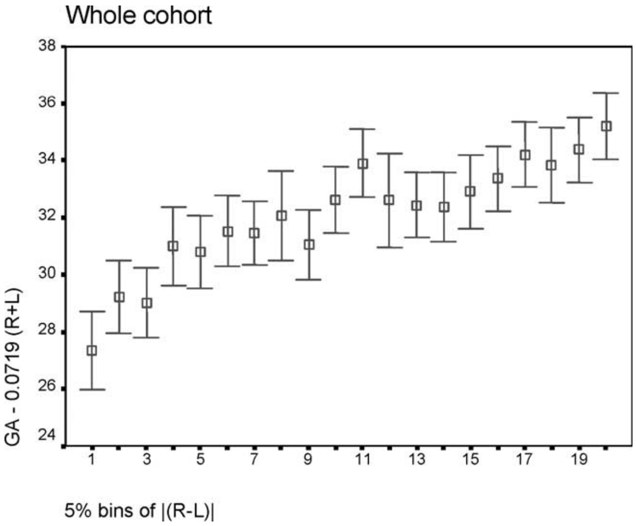

Fig. 3. Mean of General Ability, adjusted for the effect of (R + L), for the 5% bins of increasing absolute laterality, regardless of direction.

4. Discussion

The results here are free from some of the statistical problems that plagued other attempts to discern the relationship between laterality and cognitive ability. They show that there is no evidence of a cognitive disadvantage to extreme laterality in either direction. It seems likely that the Annett and Manning (1989) results were entirely due to a confound with the overall level of hand skill (R + L). This leaves Annett's balanced polymorphism model of the evolution of handedess, which depends upon penalties at the extremes of laterality, in a somewhat precarious position. In this population, the greatest cognitive *advantages* are at the extremes of handedness.

It was argued above that Crow et al.'s (1998) claim of a specific deficit close to the point of equal hand skill was suspect for statistical reasons. The present results show that the lower scores close to the point of equal hand skill are part of a more general monotonic

Table 2
Multiple regression equations for General Ability score on total hand skill (R + L) and difference in hands (R – L)

Equation	r^2	*df*
Right-hand advantage boys		
GA = 0.0676 (R + L) + 0.127 (R – L) + 30.401	0.044 (0.034)	3609
Left-hand advantage boys		
GA = 0.0571 (R + L) + 0.107 (R – L) + 31.329	0.033 (0.026)	571
Right-hand advantage girls		
GA = 0.0544 (R + L) – 0.0929 (R – L) + 34.812	0.033 (0.027)	3810
Left-hand advantage girls		
GA = 0.0778 (R + L) + 31.711	0.021 (0.021)	466
Master equation		
GA = 0.0719 (R + L) + 0.132 |(R – L)| + 28.719	0.054 (0.043)	11,977

All variables shown significantly improve the model ($p < .001$). The r^2 value in brackets is that obtained with just (R + L) in the equation.

relationship of laterality to cognitive ability which is independent of overall hand skill. It is true (Fig. 3) that the negative slope is perhaps slightly steeper close to the zero point, and this may be what Crow et al. were picking up in their original analysis. Mayringer and Wimmer's (2002) reanalysis, as we have seen, suffered from statistical problems of its own, and the effect is so weak that it is quite possible to miss it in a limited sample or with a biased measure.

The results provide statistical support for Leask and Crow's (2001) claim that laterality affects cognitive abilities. However, their conclusion that their findings bear crucially on the evolutionary origins of language and human cognition (p. 516) is perhaps somewhat fanciful. The relationship observed is indeed significant but accounts for around 1% of the variation in General Ability score (and no more of the variation in its verbal sub-scale). One can hardly argue that lateralisation to one side or the other is the main keystone of fully human cognition when people at the point of equal hand skill are comfortably within the normal range of verbal and non-verbal intelligence. Nonetheless, the basic shape of the relationship is as Leask and Crow (2001) describe.

Given the large sample size and the care taken over the statistical procedures, these results would seem conclusive. The only conceivable difficulty is that performance on the box-ticking task could be affected by different degrees of writing experience (Mayringer & Wimmer, 2002, p. 704). Thus, those who learned to write early would show a greater writing-hand advantage on the box-ticking at age 11. Since early writers are likely to be high IQ scorers, there is a possibility that the observed relationship is secondary to writing experience rather than an expression of intrinsic brain organisation. Only further developmental studies with the box-ticking task will be able to eliminate this possibility. To the present author, however, it seems unlikely, not least because 17% of those who did better with their left hand on the task in this sample actually wrote with their right hand.

How are these findings to be related to earlier claims of a left or right advantage in cognitive abilities? The fact that the left- and right-advantage equations in Table 2 do not differ significantly shows that there is no difference between left- and right-handers in the relationship between laterality and cognitive ability. However, left-handers are less strongly lateralised than right-handers ($|R - L|$, left-hand writers mean = 23.68, right-hand writers mean = 25.49; $t = -4.792$, $df = 12625$, $p < .001$). This, coupled with the relationship shown in Fig. 3, predicts a small left-hand writer disadvantage in GA score, which is precisely what is found (McManus & Mascie-Taylor, 1983). The fact that other surveys (Newcombe et al., 1975) have failed to find this effect suggest that it is too weak to be detected without a very large sample.

The most difficult results to reconcile with the present findings are those showing a paucity of extreme dextrals (Benbow, 1986), or an excess of sinistrals (Noroozian et al., 2002), amongst very high achievers. The present results show that the extremely lateralised in either direction have the highest mean IQs, so strong dextrals should be well-represented in the top of the distribution, and also that sinistrals have no mean advantage, so there is no reason to predict an excess of them in the top of the distribution. One possible explanation is that the tasks used to identify high-achievers in the two studies cited (Iranian university entrance examinations, the Mathematical and Verbal parts of the College Scholastic Aptitude Tests) do not load very highly on the general factor of IQ. Another, perhaps more general, explanation is that the variance in cognitive abilities is unevenly distributed with respect to handedness. If extreme dextrals had a small variance, then there would be few of them in the top tail despite their high mean, and similarly if sinistrals had a large variance, they could be over-represented in top tail. To test this possibility, the standard deviations of adjusted GA were compared across the sample divided into deciles on the basis of the difference between the hands ($R - L$).

The results are shown in Fig. 4. The extreme dextrals (deciles 9 and 10) do indeed tend to have smaller standard deviations in adjusted GA score than weak dextrals, mixed-handers or sinistrals (Illustrative statistics: Levene's test for equality of variances, decile 10 vs. 1; $F = 22.05$, $p < .001$; decile 10 versus 2, $F = 38.40$, $p < .001$; and decile 10 versus 4, $F = 13.57$, $p < .001$). Indeed, given that there is a concentration of sinistrals at the lower end of the distribution due to 'pathological' left-handedness (Bishop, 1984; Harris & Carlson, 1988),

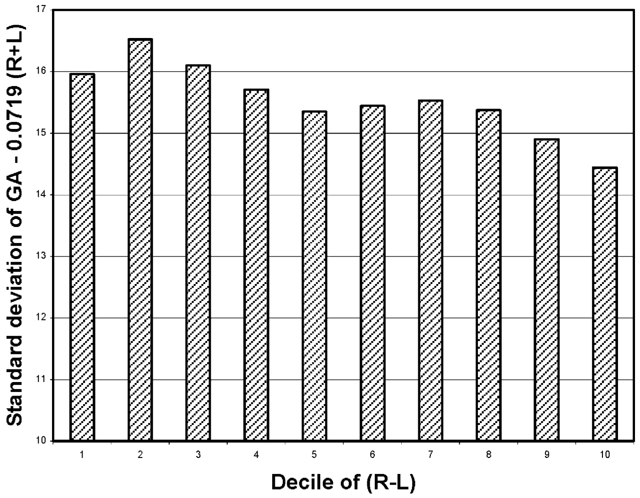

Fig. 4. Standard deviation of GA adjusted for overall hand skill ($R + L$), by decile of difference between the hands ($R - L$). Left-handers are in decile one. Decile two contains those around the point of equal hand skill.

there must be some very high-scoring sinistrals and a large standard deviation in order for the sinistral and dextral means to be as close to one another as they are.

Is this greater variance sufficient to account for the results of Benbow (1986) and Noroozian et al. (2002)? Assuming an average level of $(R + L)$, the master equation from Table 2 predicts a mean GA score of 46.71 for the most dextral decile, 45.13 for the most sinistral, and 40.14 for the decile around the point of equal hand skill. From Fig. 4, the respective standard deviations are 15.96, 16.52, and 14.44. Using the normal distribution, we can thus compute that to be in the top 1% of GA of the population, an extreme dextral has to be 1.89 standard deviations above the mean for his level of laterality. An average sinistral only has to be 1.81 standard deviations above his mean, even though his mean is lower. Note though that someone around the point of equal hand skill has to be 2.05 standard deviations above his mean. These effects are subtle, but they could account for a concentration of sinistrals and a paucity of strong dextrals amongst the extremely gifted in various fields.

In conclusion, then, in analysing the relationship between cognitive ability and hand laterality, it is important to separate both conceptually and statistically the effect of overall level of hand skill, which is positively related to IQ, from that of laterality as such. The present analysis has used stepwise multiple regression as the tool to do this. Any continuous measure of handedness used in future investigations should follow suit. Once this is done, any disadvantages at the extremes of hand laterality disappear, and the pattern observed by Leask and Crow (2001) is confirmed: average cognitive ability increases with increasingly strong laterality in either direction. The effect is highly significant but very weak (accounting for less than 1% of the variance in IQ), and will thus require very large samples to be detected. The slope is the same whether the laterality is to the left or the right. If there is a difference in mean IQ between left and right handers, it is due to left handers being less strongly lateralised. The variance in IQ is diminished amongst extreme dextrals, and this may account for the observation that extreme dextrals are under-represented relative to sinistrals in groups of very high achievers.

Appendix A. The NCDS data set

The NCDS is an ongoing, multidisciplinary longitudinal study of all the children born in Britain between 3rd and 9th March 1958. The original perinatal survey (Butler & Bonham, 1963) has been followed up by six 'sweeps', in which the cohort is recontacted every few years for more information as they grow older (Bynner, Butler, Ferri, Shepherd, & Smith, 2001; Ferri, 1993; Fogelman, 1983). The original sample contained over 17,000 babies, but about one third have been lost to follow-up over the years. It has been shown elsewhere that this loss to follow up is not entirely random with respect to IQ (Nettle, in press), with those lost to follow up having slightly lower scores. However, the bias is slight, and a wide range of IQ scores remain in the sample. Since the present study is correlational in design rather than basing its conclusions on the absolute frequencies of traits, it is not invalidated by sample attrition.

The children were tested for verbal and non-verbal intelligence at the age of 11 years (see Leask & Crow, 2001 for details). The GA score used here is the average of these scores. This measure has been shown elsewhere to have high validity and reliability (Nettle, in press) and the data have been extensively used in handedness studies (Crow et al., 1998; Leask & Crow, 2001; Mc Manus & Mascie-Taylor, 1983). The handedness task is the number of small boxes ticked with a pen in one minute using either the right or the left hand.

The data used here are the same as those used by previous investigators. However, our version (Nettle, 2002, in press) amalgamates the data from the most recent sweep (2000) with those from earlier sweeps. Although all the variables discussed in this particular paper are from much earlier, a number of records were excluded in the process of merging the databases. As a result, our sample sizes tend to be slightly smaller than those reported by previous investigators using this data set. All the phenomena they report are however found in our version of the data set.

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