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IQ, reaction time and the differentiation hypothesis

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Abstract

Associations between reaction times and mental ability test scores have been widely reported in the literature on the information processing theories of psychometric intelligence. There have been varying estimates of the strength of these associations, which are typically reported in terms of correlation coefficients. In a previous article, we reported correlations between scores on Part 1 of the Alice Heim 4 and simple and four-choice reaction time of −.31 and −.49, respectively, derived from a population based sample of 900 residents of the West of Scotland aged 56. The use of the Pearson, or product moment, correlation coefficient to summarise the association between reaction time and mental test ability assumes that they jointly have a bivariate normal distribution and that the relationship between them is linear. The differentiation hypothesis can be construed as implying that the relationship should be nonlinear with a stronger relationship at lower levels of mental ability. We examined in detail the relationships underlying these correlations to assess whether they adequately represented the strength of the association and to test for any departure from linearity. For four-choice reaction time, the correlation is a good summary of the relation to AH4 score. However, the relation of AH4 and simple reaction time is more complex and nonlinear.

Keywords: IQ; Reaction time; Alice Heim 4

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1. Introduction

Reaction time has played an important part in research on human mental ability for over a century. In the first decades of this work, studies often found faster mean reaction times to be associated with higher occupational status and greater mental ability as measured by a variety of tests (Beck, 1933; Johnson et al., 1985; Peak & Boring, 1926). Working within the information processing paradigm, Hick (1952) devised a reaction time procedure that systematically varied the number of choices to be made, including zero, the latter being simple reaction time. He found that the rate at which reaction time slowed was systematically related to the number of choices. Roth (1964) found that this 'slope' was related to mental ability differences, and his findings led Eysenck (1967) to suggest that simple reaction time was not related to mental ability test differences, but that the slope was the important causal component of the relationship. However, subsequent work has shown choice, and even simple reaction times, to be more strongly related to mental ability test scores than the Hick slope (Deary, 2000). A variety of possible causal mechanisms has been proposed as possibly underlying these associations, ranging from basic processes such as speed of information processing within the nervous system, to higher level ones such as attention, learning, and motivation (Neubauer, 1997).

A serious problem with the studies in this field of research lies in the nature of the samples studied. Typically, these tend to comprise young people with the higher levels of mental ability typical of college and university students. Consequently, Nettelbeck (1987) has called for large scale testing of normal samples of the population. In a previous article (Deary, Der, & Ford, 2001), we reported correlations between a test of mental ability and reaction times in a large ($n = 900$) population-based sample aged around 56. The scores on the first part of the Alice Heim 4 were used as the measure of mental ability. Simple and four-choice reaction times were measured on a Hick-like device. The AH4 scores correlated $-.31$ with simple reaction time and $-.49$ with four-choice reaction time. These correlations did not differ statistically among subgroups defined by sex, social class, education, or error rates in the choice reaction time. The value for four-choice reaction time is larger than the value of $-.32$ suggested by Jensen (1987). This difference could be due to the differences between the samples, together with the inexactitude involved in correcting student-dominated samples for restricted range.

An alternative possible explanation is furnished by the differentiation hypothesis. This traces its origins to Spearman's supposition that the effect of general intelligence on mental test scores would be greater at lower levels of ability and at younger ages. He referred to this as "the law of diminishing returns" (Spearman, 1926). The studies that have explored this hypothesis typically employ batteries of mental tests and examine different ability levels for differences either in the average inter-test correlations or in the proportion of variance accounted for by the first principal factor or component (see Deary et al., 1996 for further details). However, the theory could also be taken to imply that virtually any two distinct measures of mental ability would exhibit a nonlinear relationship, with a stronger association at lower levels of ability. In a population based sample, covering the full range of mental abilities, one would expect there to be a nonlinear relationship with information processing measures like reaction time, with steeper slopes at lower mental ability.

The aim of this study is to explore in detail the relationship of both simple and four-choice reaction time to AH4 score, to assess whether the correlations reported adequately represent the strength of the relationship, and to test for any departure from linearity.

2. Methods

A brief description of the sample and methods are given here. Further details are given in the earlier article (Deary et al., 2001) and in the references cited there.

2.1. The sample

The sample was derived from the West of Scotland Twenty-07 study: Health in the Community. This is a longitudinal population-based study designed to investigate socially structured health inequalities. It comprises three age cohorts who were aged around 15, 35, and 55 when the study began in 1987, drawn as clustered random samples from the Central Clydeside Conurbation, a large urban area centred on Glasgow. Comparison with data from the 1991 Census shows the achieved sample to be broadly representative of the population from which it was drawn (Der, 1998).

Interviewing for the oldest cohort began a year later than the other two when their mean age was 56.3 years (S.D. 0.6). The interview was administered in two parts and the second part included the Alice Heim 4 test of mental ability (Part I: verbal and numerical reasoning) and a task measuring simple and four-choice reaction time. (The interviews for the other two cohorts did not include the AH4, so the data for this and the earlier paper only concerns the '55' cohort.)

Whereas 1042 respondents completed the first part of the interview, only 983 completed the second part. Of these 81 did not have complete data for both the reaction time and AH4 and a further two were excluded because of excessive (>25%) errors in the choice reaction time task, leaving a working sample of 900.

2.2. The measures

Reaction times were measured using a portable device, originally designed for the UK Health and Lifestyle Survey (Cox et al., 1987). This has an LCD display screen at the top with five response buttons below it arranged in a shallow arc and labelled 1, 2, 0, 3, and 4, from left to right; Deary et al. (2001) include a diagram showing the layout. For the simple reaction time test, the respondent rests the index finger of their preferred hand on the 0 button and presses it as soon as a zero appears on the screen. Eight practice trials are followed by 20 test trials. The mean and standard deviation of these trials were recorded in milliseconds. The results of the individual trials are not stored by the device.

Four-choice reaction time involved the respondent resting the index and middle finger of each hand on the buttons labelled 1, 2, 3, and 4, and pressing the corresponding key when one of the four digits appears in the display. There were 8 practice trials and 40 test trials. During the test trials, each digit appears 10 times in a randomised order. The mean and standard deviation of reaction time are recorded separately for correct and incorrect responses as well as the number of errors. For both simple and choice reaction time, the interval between a response and the display of the next digit varied randomly between 1 and 3 seconds.

AH4 score is the total number of correct answers for Part I of the Alice Heim 4 (Heim, 1970). This is a 65-item test, with approximately equal numbers of verbal and numerical items. The items include series completion, mental arithmetic, vocabulary, and reasoning by analogy. The time limit is 10 min. There are 12 practice items. Part I of the test correlates .66 with Raven's Progressive Matrices (Heim, 1970), and the test has been used successfully in very large population cohorts as a valid measure of verbal and numerical reasoning (Rabbitt, Diggle, Smith, Holland, & McInnes, 2001).

2.3. Analysis

A range of regression-based techniques are used to model the bivariate relationships between each of the reaction time measures and AH4 score. This takes place in stages with later stages dependent on the results from earlier ones. We give an overview here and provide more details below. We begin with univariate and bivariate descriptive statistics and scatterplots. This confirms that the reaction times are positively skewed, as in commonly found, but also reveals that their variances decrease with increasing AH4 score. Under these circumstances, ordinary least squares regression may not adequately summarise the relationships observed. The combination of skew and nonconstant variance might also exaggerate any nonlinearity in the relationships. We use a procedure suggested by Box and Cox (1964) to transform the data in order to normalise the distributions and stabilise the variances. We then regress the transformed reaction times on AH4 score. A polynomial regression is used to test for nonlinearity in the relationship of the transformed reaction times to AH4 score. Finally, the adequacy of the polynomial fit is assessed by comparing the results with a locally weighted regression. The predicted values from the regressions are transformed back to the original scale (milliseconds) where necessary and plotted for comparison. To aid visual assessment of the fit, the bivariate distributions are estimated and displayed as contours on these plots.

All analyses were carried out in SAS with the exception of the Box–Cox transformation which used an S+ routine provided by Venables and Ripley (1994).

3. Results

Table 1 gives descriptive statistics for the simple and four-choice reaction times and AH4 scores. Both reaction time measures are positively skewed, particularly simple reaction time.

Table 1
Descriptive statistics for reaction time and Alice Heim 4

	Simple reaction time (ms)	Choice reaction time (ms)	AH4 score
Mean	358	728	26.7
S.D.	120	107	11.3
Skewness	2.19	1.41	0.20
Maximum	1116	1579	58
Upper quartile	394.5	781.5	35
Median	323	717	26
Lower quartile	282	659.5	19
Minimum	206	410	0

Fig. 1 shows scatterplots of both reaction time measures against AH4 score. The marginal box and whisker plots display graphically the quantiles given in Table 1, with the dashed line indicating the range of observations that could be considered outliers. These are 1.5 times the interquartile range beyond the central 50% of the data. A negative association is evident for choice reaction time, but less so for simple reaction time. For simple reaction time, there appears to be a floor effect just above 200 ms. There are a relatively large number of outliers particularly at lower AH4 scores and a strong suggestion of decreasing variance with increasing AH4 score.

This is further illustrated in Table 2, which shows means and standard deviations for the reaction time measures for approximate deciles of AH4 score. For both simple and choice reaction time, the mean and standard deviation tend to decrease with increasing AH4 score. Levene's test for the homogeneity of variance across deciles was significant ($P < .0001$) for both measures [$F(9,890) = 4.3$ for both simple and choice reaction times].

Thus the data exhibit both positive skew and heteroscedasticity. The biases that these induce can often be ameliorated by a suitable transformation. In practice, the choice of transformation is often made by trying several common forms and picking the one with the best results. For positive skew, common candidates would include the square root, log, and reciprocal transformations. Box and Cox (1964) suggest a more rigorous procedure. This is based on the family of transformations with the general form: $y^{(\lambda)} = (y^{\lambda} - 1)/\lambda$ for $\lambda \neq 0$ and $\log(y)$ for $\lambda = 0$. They suggest fitting a range of values for λ and choosing that which yields the maximum likelihood for the model in question, in this case, the regression of reaction time on AH4 score. One advantage of this is that it allows an optimal choice from a continuous range of parameter values, as opposed to a few discrete values. Another advantage is that the transformation is optimised for the model to be fitted, that is for the conditional, or error, distribution rather than the unconditional, univariate distribution of reaction times.

We used the boxcox routine of Venables and Ripley (1994) within the S+ package, which resulted in values for λ of -1.47 for simple reaction time and $-.65$ for choice reaction time. Using these values to transform the reaction times resulted in much more symmetrical distributions with skewness of .11 for simple reaction time and .62 for choice

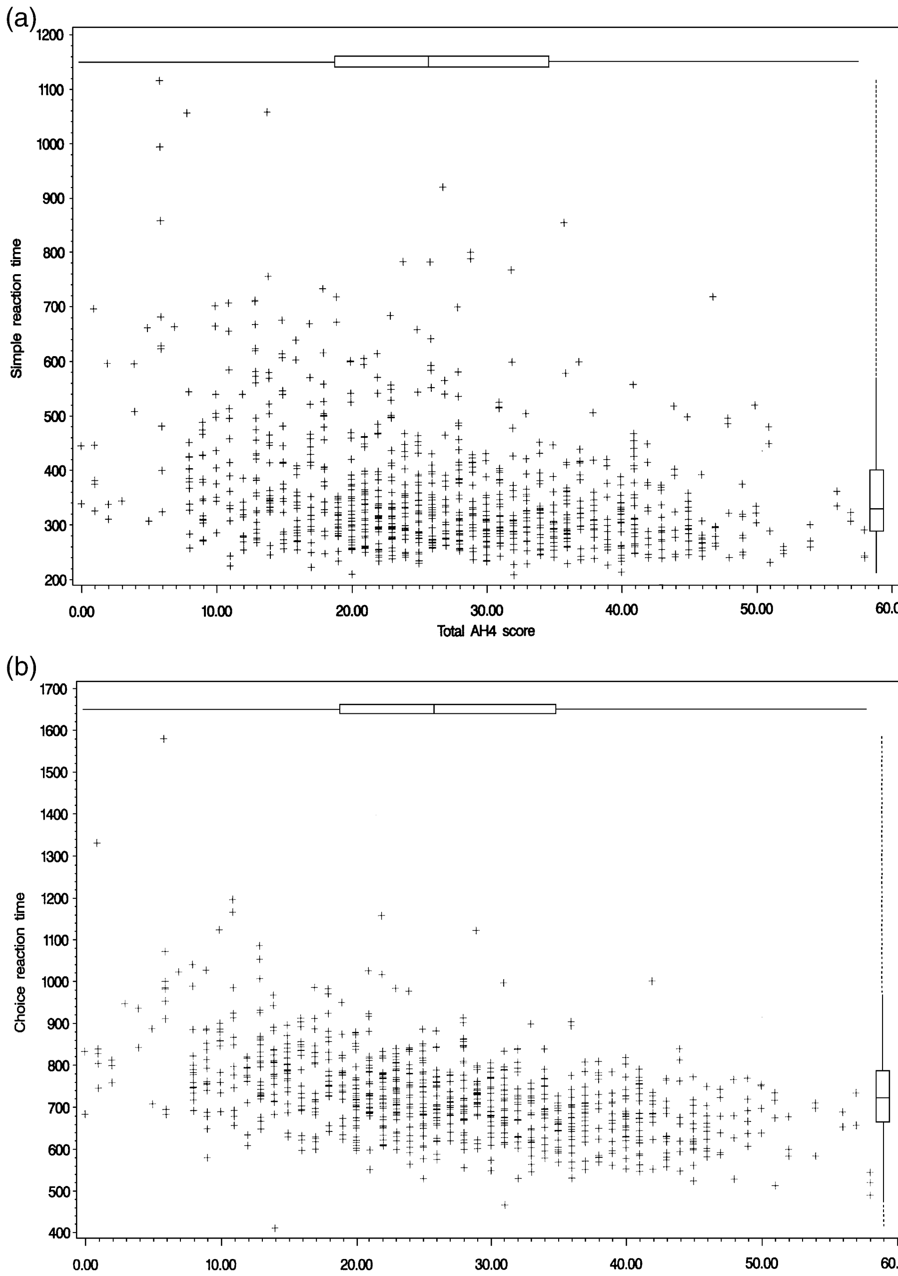

Fig. 1. Scatterplots of simple (a) and four-choice (b) reaction times against AH4 scores, with marginal box and whisker plots.

Table 2
Reaction time means and S.D. by approximate decile of Alice Heim 4 score

AH4 decile	Range		Simple reaction time (ms)		Choice reaction time (ms)		n
			Mean	S.D.	Mean	S.D.	
1	0	12	442.7	174.3	835.9	154.6	89
2	13	16	413.6	145.4	789.2	100.2	89
3	17	20	368.3	115.9	753.5	90.9	98
4	21	23	351.2	96.3	741.6	92.4	104
5	24	26	351.4	110.0	722.2	84.0	92
6	27	29	365.1	128.2	727.7	84.4	80
7	30	33	327.0	84.3	693.3	80.6	96
8	34	37	328.3	88.2	675.1	72.2	87
9	38	42	320.0	68.6	677.7	77.6	81
10	43	58	310.8	81.4	650.1	72.7	84

reaction time. Levene's test for the homogeneity of variance across the deciles of AH4 is was no longer significant for either measure [$F(9,890) = 0.69$, $P = .7$, for simple; $F(9,890) = 0.92$, $P = .5$ for choice reaction time]. Fig. 2 shows quantile plots of the residuals from regressions of the untransformed and transformed reaction times on AH4 score. A concave pattern of residuals indicates positive skew in the conditional distribution and this is evident for the untransformed simple reaction times and, to a lesser extent, choice reaction times. This confirms the impression given by the univariate distributions. The Box–Cox transformation has clearly been effective, as the residuals from the regression of the transformed reaction times closely approximate a straight line, indicating normality.

We then tested for nonlinearity, with a polynomial regression of the transformed reaction times on increasing powers of AH4 score using forward selection. The quadratic term was significant for both measures, but the cubic term did not reach significance for either ($P = .27$, simple RT; $P = .89$, choice RT).

Summary details of the regressions are given in Table 3. Because of the nature of the transformation the parameter estimates cannot be readily interpreted and have been omitted. The strength of the association between reaction time and AH4 score, implied by the R^2, is comparable to the simple correlations reported earlier, with slightly more of the variance explained by the transformed variables and the quadratic fit. Simple reaction time accounts for 10.8% of AH4 variance, with the quadratic term contributing 0.7%. Choice reaction time accounts for 24.7% of AH4 variance, with the quadratic term contributing 0.4%.

Finally, as a check that the parametric form does not unduly influence the fit, especially at the extremes, we fitted a locally weighted (loess) regression line with the equivalent degrees of freedom of a quadratic regression (Hastie & Tibshirani, 1990).

The predicted values from each of the four regressions are displayed in Fig. 3.

To aid the visual assessment of the models, the bivariate distributions of AH4 score with each of the two reaction time measures were estimated, using Kernel Density

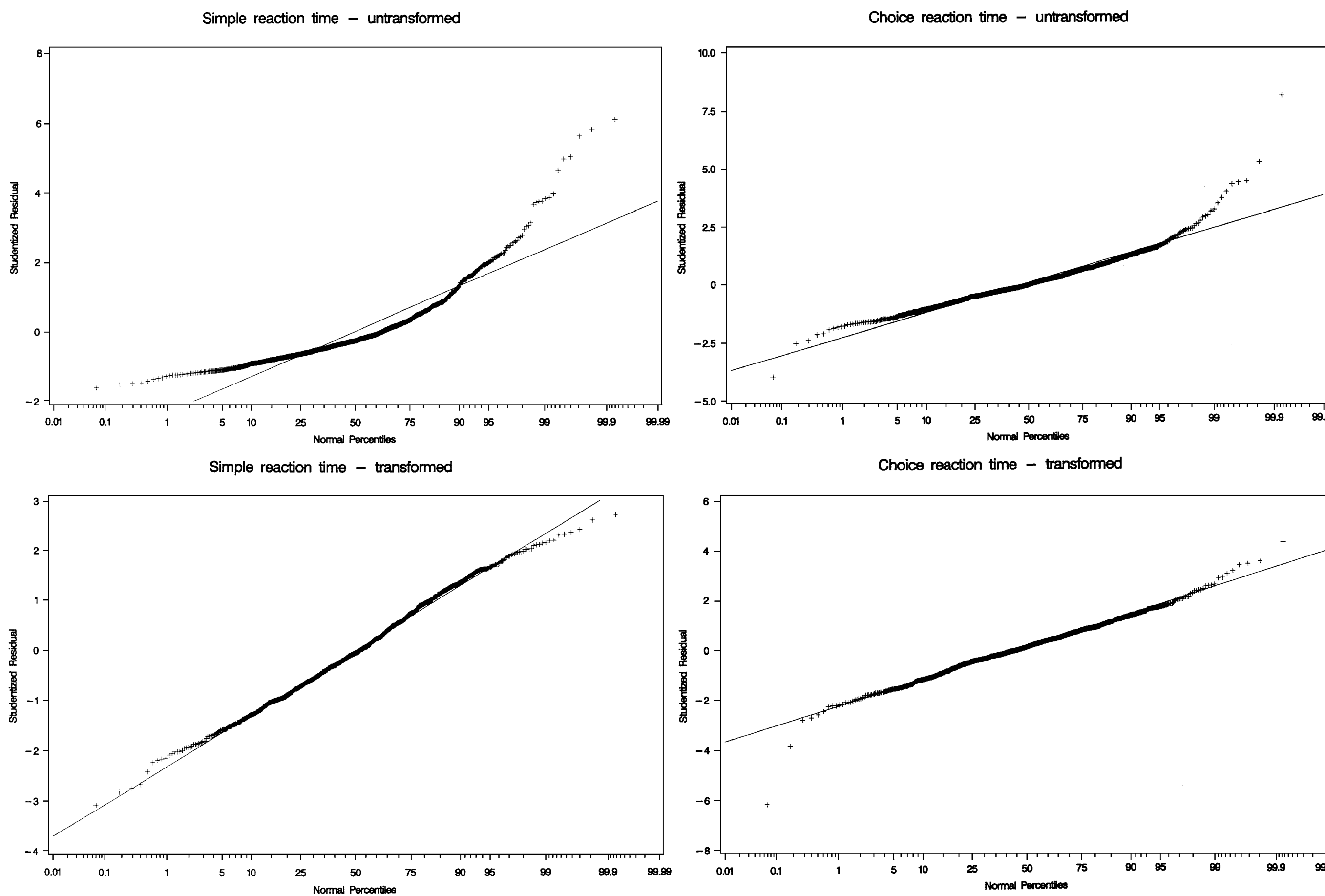

Fig. 2. Quantile plots of residuals from regressions of untransformed and transformed reaction times on AH4 scores.

Table 3
Summary statistics for polynomial regression of transformed reaction times on AH4 scores

Step	Terms in model	No. (vars in)	Partial (R^2)	Model (R^2)	F	P
Model 1: Predicting simple reaction time						
1	Linear	1	.102	.102	101.5	< .0001
2	Linear + quadratic	2	.007	.108	6.8	.009
Model 2: Predicting choice reaction time						
1	Linear	1	.242	.242	287.2	< .0001
2	Linear + quadratic	2	.004	.247	5.1	.025

Estimation and the results displayed as contours in Fig. 3. Also superimposed on the plots are the mean (circles) and median (solid squares) reaction time for each decile of AH4 score. The solid line shows the regression line of the untransformed reaction time on AH4 score. The dotted line represents the regression of transformed reaction times. The solid curve shows the quadratic regression and the dashed curve the locally weighted regression.

For simple reaction time, the decreasing variance with increasing AH4 score is evident from the contours, as is the positive skew (all the decile means lie above the medians). The contours also suggest a ‘floor’ effect, as mentioned earlier. The ordinary regression line lies some way off the peak of the bivariate distribution, contained within the innermost contour. Nor does it lie along the ridge evident to the right of the peak. In short, the ordinary least squares regression line is not a good summary of the bivariate relationship. This bias is not surprising given skewness and nonconstant variance. The regression of the transformed reaction time appears to be an improvement. The line is shallower and lies closer to the decile medians indicating that it is less influenced by the skewness and heteroscedasticity of the data. The quadratic regression depicts a relationship that is relatively flat above the mean AH4 score and steeper below it. The locally weighted regression is in close agreement, flattening out slightly less at higher AH4 scores. Both curves fit closely to the decile medians.

For choice reaction time, the contours form a pattern much closer to the series of concentric ellipses typical of a bivariate normal distribution. The positive skewness, which is lower overall than for simple reaction time, is more confined to the lower values of AH4. Apart from the lowest decile, the decile means and medians are relatively close together. As might be expected, therefore, the ordinary least squares regression of the original data is a much better summary of the relationship with AH4. Although it does not bisect the inner contour, it does appear to lie along the ridge of the distribution and to coincide with the decile means and medians. Using the transformed data gives a comparatively minor improvement. The quadratic and locally weighted regressions are again in very close agreement, the locally weighted regression being very slightly flatter at both extremes. Although the quadratic term is statistically significant, with a steeper relationship at the lower AH4 scores, the curvature is slight.

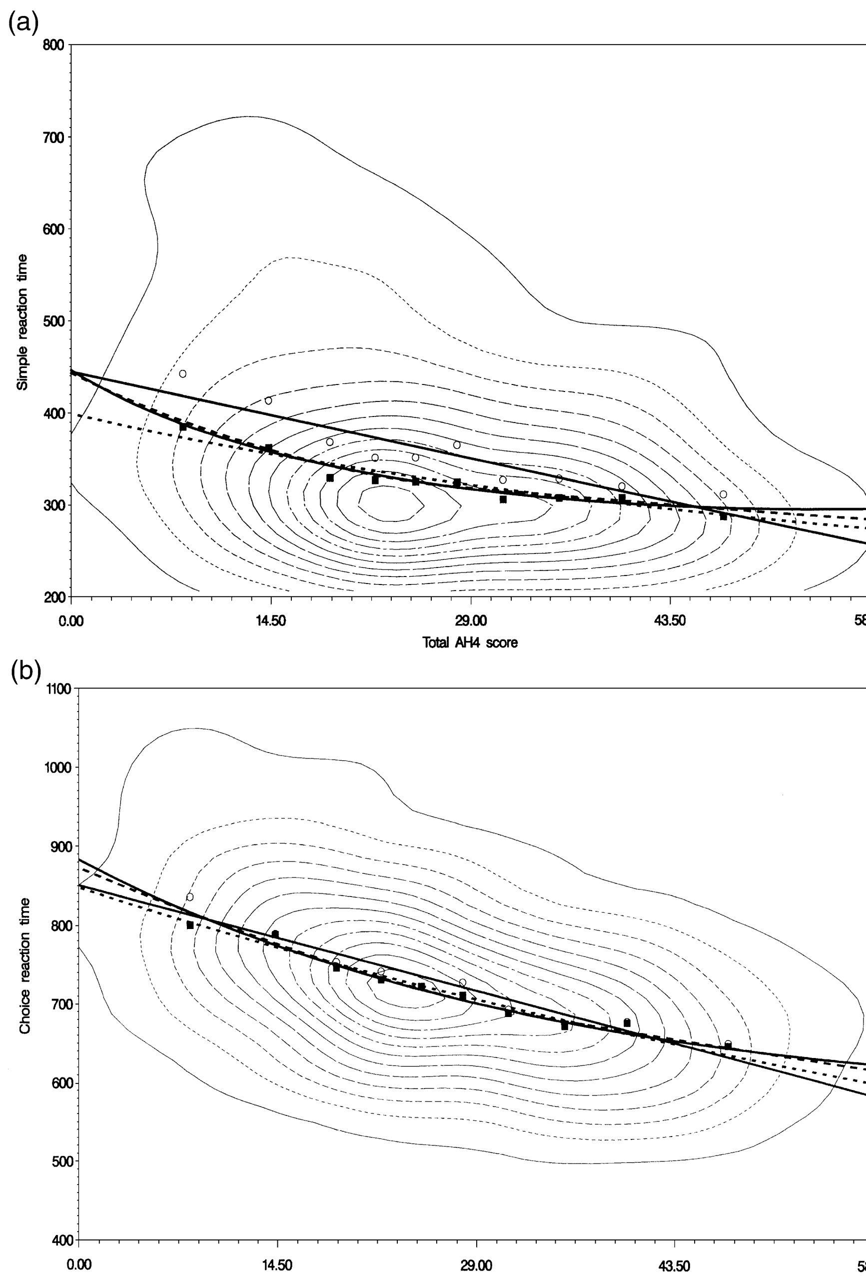

Fig. 3. Predicted values from regressions of simple (a) and four-choice (b) reaction times on AH4 scores, overlaid on contours of the estimated bivariate density and decile means (circles) and medians (solid squares).

4. Discussion

After half a century of research on the relationship of mental ability to the parameters of the Hick reaction time procedure, Roberts and Stankov (1999) could still only describe the results as "inconclusive." Although partly due to the variation in apparatus and procedures employed, this also reflects the use of small and/or unrepresentative samples. We have previously reported results from a large population-based sample aged around 56 years, with correlations between scores on Part I of the AH4 and simple and four-choice reaction times of $-.31$ and $-.49$, respectively (Deary et al., 2001). In that paper, our main concern was to describe the size of the correlations, compare them with other published results and test their stability across major sociodemographic and performance subgroups. Here, we have examined the relationships underlying those correlations in more detail.

The use of the Pearson, or product moment, correlation coefficient implies among other things that the underlying relationship is linear in form. The differentiation hypothesis (Deary et al., 1996; Detterman & Daniel, 1989), in contrast, can be taken as implying that it is nonlinear with the slope being steeper at lower levels of mental ability. This study is better placed than most to examine the issue, both because of its large sample size and its representativeness, which in turn yields a full range of mental ability test scores.

The relationship between simple reaction time and AH4 score presents a somewhat complex picture. The positive skew was to be expected, the heteroscedasticity less so. The two together upwardly bias the linear estimate of the relationship, and could give a misleading impression of a nonlinear relationship. Using the Box–Cox transformation to normalise the distribution and stabilise the variance results in a less biased linear estimate. However, it also becomes clear that the relationship is not linear, but is better described as a quadratic relationship. The locally weighted regression largely confirms this. Supplementary analyses (not shown) repeating the locally weighted regression with additional effective degrees of freedom did not materially alter this conclusion.

The other major feature of data is the apparent 'floor' effect just above 200 ms. We are not aware of this feature having been previously reported in the literature. It is important to stress that the values here are not the result of any censoring built into the apparatus, procedures, or data processing. While psychometric tests are designed with the avoidance of floor and ceiling effects in mind, this may not be possible for simple reaction time tasks. The floor effect observed here, taken together with the weaker relationship at higher ability levels, might suggest that the simple reaction time task has little cognitive load at those levels.

For choice reaction time, we find that the correlation is a good summary of the relationship with AH4, both in its form and strength. There is statistically significant departure from linearity in the relationship, but the degree of curvature is very slight. Comparison with the results for simple reaction time suggests that those are unlikely to be due to an atypical group of subjects with lower ability.

The relationship between reaction time and AH4 score described here is of the form predicted by the differentiation hypothesis. For choice reaction time, the departure from linearity, although in the predicted direction, is rather weak. For simple reaction time, it is more pronounced. This could be interpreted as showing support for the differentiation hypothesis. An alternative interpretation, alluded to above, would be that the simple reaction time task is qualitatively different at high and low ability levels. This would offer rather less support for the differentiation hypothesis. Indeed, it is tempting to speculate that the evidence for the differentiation hypothesis might largely consist of such artefacts, since both ceiling and floor effects are more likely to be observed in subtest scores than in the overall score.

The literature on reaction time and mental ability, more generally, is characterised by a range of disparate findings and resultant conclusions, particularly for simple reaction time. While Eysenck (1967) proposed that simple reaction time should be unrelated to mental ability, but that the Hick slope should be, Beauducel and Brocke (1993) report correlations of psychometric intelligence with the Hick intercept that are higher than those with the Hick slope. Empirical estimates of the correlation cover a disconcertingly wide range.

A nonlinear relationship between simple reaction time and mental ability could go some way towards explaining these differences. Samples with higher levels of mental ability would be expected to display lower correlation with simple reaction time simply because the curve is shallower at those levels. Differences in reported findings would then be, at least in part, an artefact of differences in the samples analysed. Sampling error and bias would also play a part and relatively small samples with high levels of ability might lack the statistical power to detect the weaker relationship that pertains at those levels. Likewise, if floor effects are also present, to a greater or lesser extent, in other data sets this might go some way towards explaining apparently contradictory research findings.

This study, together with our earlier results, goes some way towards answering the calls for information from large representative samples of the population (Nettelbeck, 1987). The results confirm the important role of choice reaction time while suggesting caution in the interpretation of simple reaction time until further data are available for similar samples.

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