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Reaction times and intelligence differences A population-based cohort study

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Abstract

The association between reaction times and psychometric intelligence test scores is a major plank of the information-processing approach to mental ability differences. An important but unavailable datum is the effect size of the correlation in the normal population. Here we describe the associations between scores on a test of general mental ability (Alice Heim 4, AH4) and reaction times using a 'Hick'-style device. The sample is 900 people aged 56 years who are broadly representative of the Scottish population. AH4 Part I total scores correlated − .31 with simple reaction time, − .49 with four-choice reaction time, and − .26 with intraindividual variability in both reaction time procedures. The correlation between AH4 scores and the difference between simple and four-choice reaction time was − .15. Separate analyses were conducted after partitioning the total group according to sex, educational level, social class grouping, and number of errors on the four-choice reaction time task. None of these factors significantly altered the effect sizes. This is the first report of reaction time and psychometric intelligence in a large, normal sample of the population. It provides a benchmark for other studies and suggests larger effect sizes than the majority of present studies, which are dominated by young student samples.

Keywords: Intelligence; IQ; Reaction time; Information processing

1. Introduction

Psychologists seeking the origins of human mental ability differences have had recourse to reaction time tasks for over a century. They assumed that parameters of the response to a

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simple stimulus might reveal some key limitations of nervous system functioning that contribute variance to psychometric test performance. These parameters include times of response, variability of response, and the differences in the times taken by different stimulus–response contingencies.

Key developments in the study of reaction times and cognitive ability differences began with Galton's collecting reaction time data that were later found to relate to occupational status (Johnson et al., 1985). Cattell (1890) suggested reaction times as one of his 'mental tests'. Wissler (1901) famously failed to find an association between reaction times and ability in undergraduates, though the flaws in the study afforded no other result (Deary, 1994). Peak and Boring (1926) reported a near-perfect correlation between mental ability and reaction time in five advanced students. Beck's (1933) review of over two dozen studies found a small mean association between being mentally more able and faster mean reaction time.

With the advent of information-processing models of human cognitive performance the focus of interest changed from mean reaction times to processing parameters contained within reaction time variants. Hick (1952) and Hyman (1953) described the lawful increase in response times with increases in stimulus uncertainty. Roth's (1964) results, brought to English-speaking psychologists by Eysenck (1967), were that people with higher psychometric intelligence test scores had a less steep increase in response times as the number of alternative stimuli increased. It was suggested that people with higher psychometric intelligence had a higher 'rate of gain of information'. Jensen and Munro (1979) began a more than 20-year effort to examine the associations between the 'Hick' reaction time procedure and psychometric intelligence differences (Jensen, 1998). Jensen's (1987) review of research relating psychometric intelligence to reaction times within the Hick paradigm found small (ca. .2 or less) raw correlations between psychometric test scores and mean reaction times, reaction time variability, and reaction time slope.

The most popular adaptation of the Hick reaction time procedure is the 'Jensen box', which was devised to separate the 'decision' and 'movement' components of overall response times to stimuli. The Jensen box, through attempting to separate reaction time components, might have introduced new problems with respect to strategy use (Deary, 2000, chapter 6; Smith & Carew, 1987). Hick (1952) himself and Roth (1964) used a different procedure, in which the subject's fingers were each placed on separate response buttons. Neubauer, Reimann, and Angleitner (1997) reverted to using this type of more standard 'fingers-on-buttons' response box. Apart from the uncertainty about the appropriate apparatus, the research that relates reaction times to psychometric intelligence currently tries to weather other problems. Interpretation of the correlations between reaction time indices and mental ability differences has veered from high- to low-level explanations. High-level explanations focused on aspects of the stimulus display and on subjects' levels of attention and their learning of the task through practice. Low-level explanations suggested that 'speed of information processing' might be the ingredient that causes the association. These matters were reviewed by Neubauer (1997).

Prior to explaining any association, though, a fundamental issue is the determination of the actual effect size. This most basic question — what is the size of the association between reaction time and psychometric intelligence in the general population? — is not yet answered. The majority of studies in this field are conducted on selected samples of young people at schools, colleges, and universities (Jensen, 1987). With regard to the variable in question, viz. mental ability, this group is abnormal, having a high mean and an attenuated range of mental ability test scores. In the reaction time field, and in other areas of the study of information processing and intelligence, there have been unanswered calls for large-scale testing of normal samples of the population (Nettelbeck, 1987). The aim of the present study is, for the first time, to report the correlation between a psychometric, general mental ability test and simple and four-choice reaction time and their intraindividual variabilities in a large, normal sample of the adult population.

2. Method

2.1. Subjects

The sample analysed here is drawn from the West of Scotland Twenty-07 Study, a population-based, cohort study that aims to investigate the processes by which socially structured health inequalities are created and maintained. Full details of the design and sampling have been described elsewhere (Ford, Ecob, Hunt, Macintyre, & West, 1994; Macintyre, Annandale, Ecob, et al., 1989). Briefly, the study involved a two-stage random sample of the population of the Central Clydeside Conurbation, a large urban area in the West of Scotland centred on Glasgow City. The sample contains three age cohorts who were aged 15, 35, and 55 at first interview. Those aged 55 at their first interview in 1988 undertook (i) the Alice Heim 4 (AH4) Part I test of general mental ability and (ii) simple and four-choice reaction time tasks. The analyses presented here are based on that cohort. The initial sample size of the age 55 cohort was 1042. Comparison with an equivalent sample from the UK's 1991 Census SARs (Samples of Anonymised Records) revealed no significant differences in terms of gender, social class, car ownership, or household tenure (Der, 1998). It is reasonable, therefore, to assume that the sample is representative of the Scottish population from which it was drawn.

2.2. Tests and procedure

Data were collected during the course of two interviews, typically conducted in the respondent's home. The first interview was mainly concerned with sociodemographic information. The second concentrated more on aspects of the respondent's health. A range of physical measurements also comprised part of the second interview, as did the measures of mental ability and reaction time. These interviews were conducted by nurses, who were recruited and trained specifically for the study. The measures of mental ability were the numeric and verbal sections of the AH4 Part I test. Administration and scoring were carried out as described in the test's manual (Heim, 1970).

Reaction time was measured using a portable device, originally designed for the UK Health and Lifestyle Survey (Cox, Huppert, & Whichelow, 1993). This has a high-contrast LCD display screen at the top with five response keys arranged below in a shallow arc (Fig. 1). The keys are labelled 1, 2, 0, 3, 4 from left to right. For simple reaction time, the respondent rests the second finger of their preferred hand on the central '0' key and is instructed to press it as

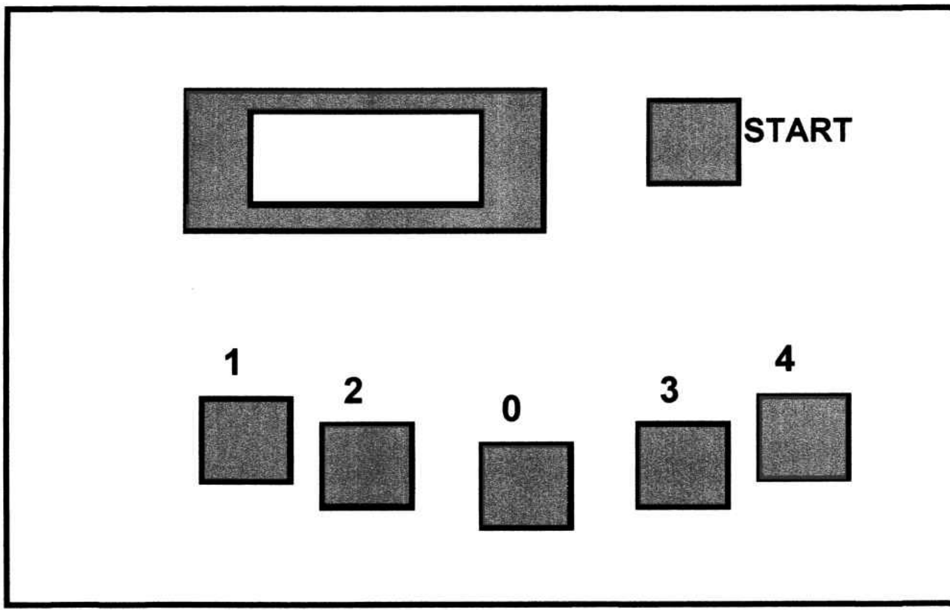

Fig. 1. The reaction time apparatus used in the present study. For the description, see text in the Method section.

quickly as possible after a zero appears in the display. There are 8 practice trials and 20 test trials. The mean and standard deviation of the test trials were recorded in milliseconds. For four-choice reaction time, the respondent rests the second (fore) and third (middle) finger of each hand on the keys labelled 1, 2, 3, 4, and presses the corresponding key when one of the four digits appears in the display. There are 8 practice trials and 40 test trials. In the test trials, the digits 1 to 4 each appear 10 times in a randomised order. Mean reaction time and the standard deviation of reaction time are recorded separately for correct and incorrect responses as well as the number of errors. The time interval between a response and the display of the next digit varied randomly between 1 and 3 s for both simple and four-choice reaction times. Total time for testing reaction times was between 10 and 15 min.

The social class of the head of household, using the traditional sixfold classification, was derived according to the United Kingdom Registrar General's Classification of Occupations (OPCS, 1980). Women are classified by their partner's occupation if married or cohabiting. Where the head of household was not working, the last occupation was used. In terms of education, the sample was simply divided according to whether they had any formal academic qualifications, or not. The fact that three-quarters had none accurately reflects the educational system and opportunities available to this age group.

2.3. The working sample

Although 1042 respondents completed the first interview, only 983 were available for the second interview. Of these, 74 did not complete the AH4 test, a further 7 had missing reaction time data, and 2 more were excluded because their error rate in the four-choice reaction time

Table 1
Mean (S.D.) Alice Heim and reaction time results for the total sample (N=900) and men (n=413) and women (n=487) separately

	Total sample	Men	Women	P for sex difference
AH4 Total	26.7 (11.3)	27.2 (11.4)	26.2 (11.3)	.17
AH4 Verbal	13.8 (5.5)	13.9 (5.5)	13.8 (5.6)	.75
AH4 Numerical	12.9 (6.2)	13.4 (6.2)	12.4 (6.2)	.03
Simple RT	358.2 (119.7)	356.4 (114.1)	359.7 (124.3)	.68
Simple RT S.D.	91.4 (63.5)	88.8 (58.4)	93.6 (67.5)	.25
Choice RT	727.8 (107.5)	727.7 (105.7)	728.0 (109.1)	.97
Choice RT S.D.	131.1 (35.5)	123.9 (33.5)	137.2 (36.1)	< .0001
CRT−SRT difference	369.7 (103.0)	371.3 (102.2)	368.3 (103.8)	.66

task was above 25%. This left a working sample size of exactly 900 subjects. The mean age at the second interview was 56.3 years with an S.D. of 0.6 and a range from 54.5 to 58.5 years. Those omitted from the working sample contained a significantly higher proportion from households of manual social class (70% vs. 57%). Nevertheless, their omission did not result in a significant difference between the working sample and a comparable sample drawn from the UK's 1991 Census SARs (62% vs. 57%).

3. Results

Mean (S.D.) total score for the AH4 test was 26.7 (11.3), and for the Verbal and Numerical subsections was 13.8 (5.5) and 12.9 (6.2), respectively (Table 1). Mean simple reaction time was 358.2 ms (119.7) with a mean intraindividual S.D. of 91.4 (63.5). Mean four-choice reaction time was 727.8 ms (107.5), with a mean intraindividual S.D. of 131.1 ms (35.5). The mean difference between simple and four-choice reaction time was 369.7 ms (103.0). Social class and years of education correlated with Alice Heim total scores at .45 and .50, respectively. Because of the total sample size, significance levels for the effect sizes are superfluous. Table 1 shows means and standard deviation separately for men and women. The only significant differences were men's slightly higher mean Alice Heim Numerical scores (t=2.20, df=898, P=.03; effect size of difference=.09 of a standard deviation), and their lower four-choice reaction time intraindividual variability (t=5.69, df=898, P < .0001; effect size of difference=.38 of a standard deviation).

The correlation between simple reaction time and AH4 total score for the whole sample (N=900) was −.31. For four-choice reaction time, the correlation was −.49. The difference between these two correlations is highly significant (t=5.62, df=897, P < .00001). The intraindividual variability (standard deviation) of simple and four-choice reaction times both correlated −.26 with AH4 total scores. The difference between the simple and four-choice reaction times correlated −.15 with AH4 total scores; people with higher AH4 test scores had a smaller increment on average. The correlation between AH4 test scores and the number of errors made in the four-choice reaction time test was .07.

Table 2
Correlations between AH4 (Total, Verbal, and Numerical scores) test scores and simple (SRT) and four-choice group ($N=900$) and for subgroups based on (i) CRT error rates, (ii) sex, (iii) social class (1 = *professional*)

	SRT mean			SRT S.D.			CRT mean		
	AH4 Total	AH4 Verbal	AH4 Numerical	AH4 Total	AH4 Verbal	AH4 Numerical	AH4 Total	AH4 Verbal	AH4 Numerical
Whole sample ($N=900$)	−.31	−.29	−.30	−.26	−.25	−.25	−.49	−.46	−.48
No errors ($n=592$)	−.32	−.30	−.32	−.30	−.27	−.30	−.49	−.45	−.48
One to five errors ($n=308$)	−.28	−.29	−.26	−.18	−.20	−.15	−.50	−.49	−.48
Men ($n=413$)	−.26	−.23	−.28	−.26	−.24	−.27	−.44	−.41	−.44
Women ($n=487$)	−.34	−.34	−.32	−.26	−.25	−.24	−.53	−.50	−.51
Social class 1 ($n=62$)	−.32	−.33	−.28	−.11	−.13	−.09	−.62	−.51	−.66
Social class 2 ($n=194$)	−.22	−.18	−.25	−.15	−.14	−.15	−.38	−.36	−.38
Social class 3 ($n=129$)	−.19	−.13	−.21	−.14	−.09	−.16	−.46	−.43	−.44
Social class 4 ($n=305$)	−.28	−.26	−.26	−.26	−.24	−.26	−.43	−.40	−.42
Social class 5 ($n=139$)	−.30	−.29	−.28	−.40	−.39	−.36	−.46	−.41	−.44
Social class 6 ($n=71$)	−.28	−.30	−.23	−.27	−.26	−.27	−.32	−.35	−.27
No educational qualification ($n=696$)	−.28	−.27	−.27	−.27	−.25	−.26	−.46	−.44	−.44
Any educational qualification ($n=204$)	−.23	−.20	−.25	−.15	−.15	−.14	−.39	−.34	−.40

Separating the AH4 into its verbal and numerical subscores did little to alter the effect sizes (Table 2).

The size of the sample allowed an investigation into the alterations of the effect sizes after controlling for certain experimental and demographic factors. Controlling for error rates in the four-choice reaction time procedure addresses the issue of speed−accuracy trade-offs, though over 77% of the subjects made no errors. Controlling for education and social class is important because these factors correlate significantly with AH4 total scores with moderately high effect sizes, as seen above. Correlations of education and social class with simple reaction time were −.19 and −.18, respectively, and with four-choice reaction time were −.25 and −.27, respectively ($N=900$ for all analyses).

Table 2 shows the correlations between AH4 scores and the reaction time measures for the whole sample and for the sample partitioned by (i) four-choice reaction time error rates, (ii) sex, (iii) social class, and (iv) educational attainment. Within each of these factors

(CRT) reaction times' means and standard deviation, errors on CRT, and CRT – SRT difference for the whole 6 = *nonskilled manual*), and (iv) educational attainments.

CRT S.D.			Error			CRT – SRT difference		
AH4 Total	AH4 Verbal	AH4 Numerical	AH4 Total	AH4 Verbal	AH4 Numerical	AH4 Total	AH4 Verbal	AH4 Numerical
– .26	– .24	– .26	.07	.07	.07	– .15	– .14	– .14
– .24	– .22	– .24	–	–	–	– .09	– .09	– .09
– .30	– .29	– .29	.08	.07	.08	– .30	– .28	– .29
– .25	– .23	– .25	.07	.08	.06	– .16	– .16	– .15
– .26	– .26	– .24	.07	.05	.09	– .14	– .12	– .15
– .32	– .24	– .36	.29	.22	.33	– .13	– .04	– .19
– .26	– .25	– .25	.01	.02	.00	– .15	– .17	– .12
– .29	– .23	– .31	.13	.17	.08	– .26	– .28	– .22
– .21	– .18	– .21	.11	.11	.10	– .09	– .08	– .09
– .30	– .31	– .26	– .01	– .07	.05	– .12	– .08	– .13
– .15	– .17	– .12	– .07	– .07	– .07	– .05	– .05	– .05
– .25	– .23	– .24	.08	.07	.09	– .15	– .14	– .14
– .19	– .15	– .20	– .00	– .00	– .00	– .14	– .13	– .13

separate correlation matrices were calculated for their constituent subgroups and were formally tested for equality using structural equation modelling. This followed the procedure described by Bentler (1995) of fitting a model that constrains each element of the correlation matrix to be equal across subgroups. The AH4 total score and the simple vs. four-choice reaction time difference were omitted from this comparison, as their inclusion would have led to computational problems. All of these models had excellent levels of fit as indicated by the Comparative Fit Index, with values of .98 for the social class comparison and > .99 for the others, suggesting that any subgroup differences are due to sampling variation.

Within the same modelling procedure, more detailed and specific comparisons may be made using the Lagrange Multiplier to test the appropriateness of the constraints imposed. In the context of these models, each constraint tested corresponds to a test of the equality of a particular correlation for a given pair of subgroups. The results of these tests have to be treated with some caution because of the large number of tests and the consequent risks of Type I errors. We examined the Lagrange multiplier tests for all correlations between the two AH4 subscale scores and any of the five basic reaction time measures. There were no significant subgroup differences for error rate, sex or educational attainment. The social class comparisons did produce two significant results with χ^2 values of 5.23 and 4.57 ($df=1$, $P=.022$ and .032, respectively). However, considering that there are 50 tests involved in the social class comparisons, these isolated results do not support systematic subgroup differences.

4. Discussion

Roberts and Stankov (1999, p. 5) described the research on psychometric intelligence and Hick reaction time parameters as "inconclusive". In part, this was because of experimental confounds introduced by different reaction time apparatus and procedures. Inconclusiveness reigns because, in addition, the area lacks 'benchmark' studies that offer accurate estimates of effect size under standardised conditions. The present study does not address all of the many issues abroad in the reaction time–psychometric intelligence field, but it provides a novel contribution nevertheless. It offers a relatively error-free estimate of the correlation between psychometric intelligence differences and simple and four-choice reaction times and their variabilities in a normal, age-homogeneous sample of the population of Scotland. The effect sizes were not significantly altered by sex, social class, education, or error rates in the four-choice reaction time task. The effect size of the association between AH4 scores and four-choice reaction times was relatively large, almost .5, probably because most studies to date have employed samples with attenuated ability variance. Correcting the present study's correlation — assuming, say, reliabilities of .85 for both reaction times and mental test scores — would increase the estimate to .53.

This effect size estimate for the correlation between psychometric intelligence and four-choice reaction time is larger than that suggested in Jensen's (1987) quantitative review. He found a corrected (for restriction of ability range and unreliability in the measures) correlation of −.32 between decision time and intelligence (see Deary, 2000, Table 6.1). This includes choice and simple decision times. Jensen's (1987, Table 2) review of 33 samples contained only two small ($N=40$ and 46) samples of "average adults", tested by Barrett, Eysenck, and Lucking (1986). In these samples, the correlations between intelligence and four-choice reaction time were −.19, −.39, −.45, and −.47. Correcting student-dominated samples for restriction of range is an inexact way of estimating normal population effect sizes and Jensen (1987, p. 157) remarked that, "These corrected coefficients may be viewed as rather conservative estimates of the population correlations of the Hick parameters with psychometric *g*." Another reason that the effect size estimates might be smaller when derived from student samples is the finding that *g* accounts for less of the variance among high ability than low ability subjects, and that psychometric tests correlate lower with information-processing variables in high- vs. low-ability samples (Deary et al., 1996; Detterman & Daniel, 1989; Legree, Pifer, & Grafton, 1996).

Though a proper 'Hick slope' measure was not computed here, the current data agree with literature reviews suggesting that reaction times and their variabilities are stronger correlates of mental test scores than are 'slope' or difference measures (Jensen, 1987; Neubauer, 1997; though see Jensen, 1998 for a defence of and some remedies for the Hick slope). In part, this is because slope and difference measures are relatively unreliable. In the present study, the correlation between simple and choice reaction time for the total sample of 900 subjects was .59. This relatively high correlation between these variables limits the reliability of the difference between them and, hence, the correlation between their difference and other variables. Assuming reliabilities of .85 for simple and choice reaction times then the reliability of their difference is .63.

The effect sizes reported here apply within the confines of the sample and the procedures. The sample was of 56-year-olds; it will be interesting to discover the variation in effect size within age-homogeneous samples of different mean ages. Note, though, that the present study's effect sizes are not caused by age differences; the results occurred within a narrow age range.

Eysenck (1967) suggested in his seminal paper that simple reaction time was not related to mental ability test differences, and that it was the slope parameter within the Hick task, related to the subject's 'rate of gain of information', that was the causal ingredient of the correlation. In the decades since then it has become clear that the Hick slope parameter has no special association with ability test scores and that choice and even simple reaction times do better (Deary, 2000, chapter 6; Jensen, 1987; Neubauer, 1997). Thus, like others, Beauducel and Brocke (1993) reported correlations between the Hick intercept and psychometric intelligence test scores that were higher than those with the slope of the Hick procedure. Mean reaction times and their variabilities afforded associations from below .2 to about .4. Simple reaction time was about as highly correlated as more complex conditions. There was a near-zero correlation between the Hick slope and psychometric intelligence test scores, and the authors commented that,

> Applying Hick's law is not necessary for finding and theoretically explaining RT $\times$ IQ correlations. (p. 635)

In the wake of the failure of reaction time-'slope' and -change measures to provide processing parameters that show strong associations with psychometric intelligence (Deary, 1997, 2000; Lohman, 1994, 1999), the present results offer support to those who are taking a new look at mean reaction times and their variabilities as the key correlates of higher level mental ability differences.

The causes of the correlations reported here are the interesting issues for future research. As the research debate stands, the causes might be related to: bodily integrity very generally (as measured by biomarkers; Anstey & Smith, 1999); more narrowly, to some 'common cause' in the nervous system that affects both psychometric test scores and reaction times (Baltes & Lindenberger, 1997); more narrowly still, to speed of information processing within the nervous system (Neubauer, 1997); or, rather differently, to some higher level function such as attention, learning, or motivation (see Neubauer, 1997). The present results provide a firmer empirical foundation than has been available heretofore from which to pursue these different, but not exclusive, causal suggestions.

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