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REDUCTIONISM AND INTELLIGENCE: THE CASE OF INSPECTION TIME

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Introduction

Successes in science tend to be successful attempts at reduction and causal interaction. The reduction of the interaction of bodies to the laws of motion and the reduction of chemical phenomena to elements and their interactions are good examples. In these cases reductionism leads to observed phenomena being explained by a relatively small number of basic concepts and the laws which govern the interaction of the concepts. The spectrum of inquiry that stretches from common sense to scientific psychology is infused with a tendency toward reductionism. Hippocrates and Galen originated and developed, respectively, the notion that temperamental differences might be reducible to the amounts of four bodily fluids, or humours (black bile, yellow bile, blood and phlegm), that a person produced. Astrologers reduced stable personality differences to the positions of the stars and planets at the time of birth. And differential psychologists have reduced the personality trait adjectives contained in the lexicon to about five major dimensions.

Therefore, it is to be expected that prominent molar phenomena will invite, however prematurely, molecular level explanations. An obvious candidate for such reductionist tendencies has been individual differences in human mental ability differences. In this paper some of the problems for the reduction of human intelligence differences will be documented and examined by focusing on the phenomenon of inspection time (IT).

Within the broadly reductionist approach to intelligence differences there are at least two discernible levels of investigation. First, there is the physiological approach. Studies in this mode examine the association between individual differences in mental test scores and indices such as brain size, head size, nerve conduction velocity, cerebral blood flow (measured by one of the functional brain scanning techniques such as positron or single photon emission tomography), latency or amplitude of the brain electrical potentials evoked by a stimulus, and electroencephalographic measurements (Vernon, 1993). When significant associations are discovered between IQ-type test scores and physiological measures the investigator is left with the problem that the two phenomena are conceptually so far apart that some connecting principle must be found. Thus, vaguely thought out notions such as 'neural efficiency' are invoked to explain the correlation. In fact, such a concept has been used to explain the associations found between ability test scores and evoked potentials and functional brain scanning (Deary & Caryl, 1993). Such terms can at worst be a mask for ignorance and at best

may be used to generate hypotheses. The point that will be emphasised in this paper is that any correlation between intelligence and a putatively lower level variable, once established as proven, must thereafter become the object of research in itself; intuitive guesses as to the construct that links the two variables must be verified in empirical studies.

The second reductionist approach to intelligence differences may be called cognitive reductionism. Here, the object is to discover whether there are any basic cognitive functions or components that are correlated with intelligence differences (Vernon, 1987). On the face of it, explaining any such association should be easier than that between IQ-type scores and physiological measures. After all, if the variance in a cognitive test assesses reliable individual differences in a validated micro-level cognitive process then it remains merely to be demonstrated how such a process plays a part in solving mental test items. However, the problem in this approach is the difference between a psychological task and the psychological construct which it is intended to assess. For example, much interest centred on the association between psychometric intelligence and individual differences in the Hick reaction time (Hick RT) measure (Jensen, 1987). The interest in Hick RT arose initially because it was discovered that within-individual reaction times increased regularly with increases in stimulus uncertainty (Hick, 1952). Therefore, an individual's Hick RT gradient (the rate of increase in response time as the number of stimulus alternatives increased) became associated with the psychological concept known as the 'rate of gain of information' (Roth, 1964). In fact, early research did find a significant association between the Hick slope and IQ-type test scores. However, as studies have accumulated it has become clear that many of the indices that can be distilled from the Hick task—such as the mean decision time, the mean movement time, intra-individual variability, etc.—correlate as high or higher than the gradient with mental test scores, and that these correlations rarely exceed 0.2 to 0.3 (Jensen, 1987). Therefore a task providing an index linked to a single psychological construct has had to be re-evaluated, and a clear explanation for the association between Hick RT and intelligence remains elusive.

The simple message from this brief introduction is that there are problems of explanation for those who attempt to discover what lies below measured intelligence. For the biological/physiological approach, a main difficulty will be the conceptual distance between the correlated variables, and the potentially long causal chain that must be unravelled. For the cognitive reductionist, there is the problem of finding out whether a cognitive task assesses any truly basic cognitive process and, in addition, of finding out how any basic process is executed by the brain.

The quest

A discriminating intelligence?

Since the beginning of the scientific study of mental ability differences there has been a tendency on the part of researchers to explain intelligence in terms of putatively lower-level psychological processes. The two founding fathers of intelligence research, Galton and Spearman, thought that brighter individuals owed their advantages to an ability to make fine sensory distinctions. Galton (1883) thought that 'the more perceptive the senses are of difference, the larger is the field upon which our judgement

and intelligence can act'. However, the evidence that Galton mustered to support his discriminative theory of intelligence was anecdotal and reflected the prejudices of the times:

'The discriminative faculty of idiots is curiously low; they hardly distinguish between heat and cold, and their sense of pain is so obtuse that some of the more idiotic seem hardly to know what it is . . . The trials I have as yet made on the sensitivity of different persons confirms the reasonable expectation that it would on the whole be highest among the intellectually ablest. . . . I found that as a rule men have more delicate powers of discrimination than women, and the business experience of life seems to confirm this view. The tuners of pianofortes are men, and so I understand are the tasters of tea and wine, the sorters of wool, and the like. These latter occupations are well salaried, because it is of the first moment to the merchant that he should be rightly advised on the real value of what he is about to purchase or to sell. If the sensitivity of women were superior to that of men, the self-interest of merchants would lead to their being always employed; but as the reverse is the case, the opposite supposition is likely to be the true one.

Ladies rarely distinguish the merits of wine at the dinner-table, and though custom allows them to preside at the breakfast-table, men think them on the whole to be far from successful makers of tea and coffee.' (Galton, 1883).

Spearman, in his mammoth article of 1904 which may be seen as the start of serious research in differential psychology, provided evidence to support Galton's idea. It is ironic, given the content of the present paper and Professor Rabbitt's (this volume) that, prior to his own investigation, Spearman stated that, 'in spite of the many previous inconclusive and negatory verdicts, the question of correspondence between the tests of the laboratory and the intelligence and will cannot yet be regarded as definitely closed'; 90 years on the same issue is being discussed. With regard to which basic psychological processes to choose in order to understand intelligence, Spearman's rationale was:

'As regards the nature of the selected Laboratory Psychics, the guiding principle has been the opposite to that of Binet and Ebbinghaus. The practical advantages proffered by their more complex mental operations have been unreservedly rejected in favour of the theoretical gain promised by the utmost simplicity and unequivocality; there has been no search after condensed psychological extracts to be on occasion conveniently substituted for regular examinations; regardless of all useful application, that form of physical activity has been chosen which introspectively appeared to me as the simplest and yet pre-eminently intellectual. This is the act of distinguishing one sensation from another.' (Spearman, 1904).

Spearman (1904) found modest correlations (from about 0.2 to over 0.4) between fineness of sensory discrimination in various modalities and teachers' estimates of general intelligence and school examination marks. These were, in general, replicated by Burt (1909–10). A critical review of this and later research in the same vein (e.g. Raz, Willerman & Yama, 1987) has shown that there are consistent but low associations between sensory discrimination and intelligence throughout the literature (Deary, 1994).

Quick on the uptake?

From the originators of cognitive reductionism in intelligence research, attention will now turn to another line of investigation within this tradition. From before

research on intelligence began until the present day there have been common-sense notions to the effect that brighter people are somehow quicker. When Hobbes (1885) discussed the 'virtues intellectual' in *Leviathan* in 1651 he reduced intelligence differences to the functioning of two basic processes:

'This "natural wit" consisteth principally in two things, "celerity of imagining," that is, swift succession of one thought to another, and steady direction to some approved end. On the contrary, a slow imagination maketh that defect, or fault of the mind which is commonly called "dulness," "stupidity," and sometimes by other names that signify slowness of motion, or difficulty to be moved.' (Hobbes, 1885).

The quest under present consideration is the attempt by researchers to operationalise this 'celerity of imagining'. There is a long list of psychological techniques that have been employed to track down the source of the speed involved in human intelligence. Some of these are reviewed in depth in Vernon (1987), and prominent among them are the Hick reaction time procedure, S. Sternberg's memory scanning test and R. J. Sternberg's analogical reasoning components. The attempt to find a psychological test that will deliver individual differences in some basic index of information processing was thought by Hunt (1980) to be futile:

'A naive, but common, way of studying individual differences in cognition is to establish a statistical relationship between performance on psychometrically defined intelligence tests and performance on more theoretically defined laboratory tasks. While these studies should aid in advancing our understanding of the relationship between psychometric and information processing theories, the results do not indicate that they will produce a major breach in the 0.3 barrier. They may push it back to 0.4, but the search for the "true" single information-processing function underlying intelligence is as likely to be as successful as the search for the Holy Grail.' (Hunt, 1980).

This quotation, however, may be used as a starting point to construct a list of desiderata for evaluating the success of the cognitive reductionist's efforts. It is most unlikely that any one information processing index will ever explain more than a minority of the variance in human mental ability. To warrant further attention, the association between psychometric intelligence and any given laboratory task might be asked to meet the following demands (with apologies to Koch's postulates).

1. The laboratory task should assess a validated psychological process; that is, it should have an established theoretical rationale.
2. The correlation between the laboratory task and psychometric intelligence scores should breach Hunt's (1980) 0.3 or, better still, 0.4 barrier.
3. It should be shown that individual differences in the laboratory task are not merely the consequence of higher intelligence; that is, it should be demonstrated that the individual differences in the laboratory task are partly causal to later intelligence differences.
4. A mechanistic explanation for the association between psychometric intelligence and the laboratory task should be provided.

These are not going to happen in the short term. Even these reasonable demands represent a massive task for any laboratory and make explicit the potential pitfalls in this type of research. It becomes clear that correlational studies are important, but that

they merely establish an association and leave much work undone. Explaining any such correlation is going to be the more arduous and time-consuming job. Premature (from the armchair) explanations or explaining-away of the association may be equally harmful: complacent acceptance of a common-sense construct (e.g. 'mental speed') as the basis of the correlation may prevent deeper understanding; and dismissals of the association as being due to some untested speculation (e.g. 'clever people are good at any old task') may kill an interesting line of inquiry before it can be investigated. Of course, it is natural, and demanded by journal referees, that one should hypothesise on the causal association involved in a correlation, but the work of establishing a valid causal chain is slow.

The task

Precedents

The task to which the above postulates will be applied is inspection time (IT). The task was devised by Vickers and his colleagues (Vickers, Nettelbeck & Willson, 1972) in the late 1960s and early 1970s. However, tasks with a resemblance to IT had been developed much earlier and were associated with individual differences in intelligence. The similarity which runs through these various tasks is that they attempt to discover how long a subject needs to see a stimulus in order to make a simple discrimination. In the tasks to be discussed the speed of the subject's reactions plays no part; none of them involves reaction times.

Cattell (1886a,b) carried out reaction time experiments with Wundt in Leipzig. As was common at the time, he devised complications of the reaction time procedure in order to discover how much longer reactions took when some extra mental processing was required. With the availability of an early type of tachistoscope, Cattell studied how much time it took various people to make a simple discrimination (Deary, 1986). Instead of asking his subjects to respond quickly, he manipulated the duration of the stimulus and asked them to state whether what they had seen was one thing or another. At first he had them discriminate a colour from a standard grey, and then moved on to letters and words. He found that the rank order of subjects was stable as they moved from colour to colour and from colours to letters and words. Cattell's papers only hint at the possible relationship between what he called 'perception time' and intelligence. After reporting results on students he remarked that:

'I tried to make the determinations on two rather obtuse porters, but their consciousness did not seem able to take up at all such delicate impression. They required three times as long as educated people to read a word.' (Cattell, 1886b).

When Cattell returned to Columbia and had his student Wissler (1901) examine the association among higher and lower level ability, he employed simple reaction time and not perception time and the measure was never revived. In work unrelated to Cattell's, Griffing (1895) discovered that the number of letters reported after a 100-msec exposure was related to mental ability as estimated by teachers. Later, Burt (1909-10) found that the number of 25-msec exposures that schoolboys required in order accurately to report a pattern of dots was related to teachers' estimates of intelligence. Although they did not cite Burt's study, Livson & Krech (1956) reported similar findings.

Single studies such as these provide interesting historical precedents for studies of inspection time. They warn also that interesting findings are liable to be left without being followed up unless they attract a group of researchers.

Basic description of IT

The measure called inspection time arose from two connected areas: theories of visual perception and theories of decision-making. In line with theories of visual perception that employ the notion of the perceptual moment, Vickers argued that the early stages of visual processes might be quantal, i.e. that visual information was encoded in snapshots, each with a small and fixed duration (Vickers *et al.*, 1972). In addition, he hypothesised that, when a visual discrimination was to be made between two alternatives, the information gathered from a briefly presented stimulus was shared between two counters, each representing one of the stimulus alternatives. When the amount of information in one of the counters passed a decision threshold the subject made a response favouring one of the stimulus alternatives. When the stimulus duration was very brief, and the information from the stimulus alone was insufficient to allow the decision threshold to be reached, the subject 'supplemented' the information intake to the counters by sampling from the (uninformative) backward mask that follows the stimulus. Vickers argued, therefore, that the stimulus duration that a given subject requires in order to make a simple discrimination to a given accuracy level should be characteristic for the individual. In addition, he argued that the function obtained when stimulus duration is plotted against discrimination accuracy should be described by a cumulative normal ogive.

The most commonly used IT task involves two parallel, vertical lines with one line longer than the other. The difference in the size of the two lines is so large that the discrimination is error free when subjects view the stimulus without limit of time. The discrimination is made more difficult by limiting the stimulus duration and by showing a backward mask immediately after stimulus offset. Therefore, all that is required of a subject in an IT task is to state which of two lines of markedly different lengths is longer. Subjects view the lines, with the long line sometimes on the left and sometimes on the right, at a variety of stimulus durations. An estimate of a person's IT is the duration required in order to achieve a given level of accuracy (often set at around 75–90%).

Establishing the association

Nettelbeck and Lally (1976; Lally & Nettelbeck, 1977) first studied the association between IQ and IT. In a study that had few subjects and a very wide range of ability (they included people with mental handicap in addition to a wide range of non-handicapped people), they found correlations of -0.8 to -0.9 between Wechsler Performance IQ and IT; brighter individuals required lower stimulus durations to make accurate discriminations. An early review of nine studies (including some unpublished undergraduate theses) still suggested a correlation in the region of -0.8 (Brand & Deary, 1982). Because these studies often included people with and without mental handicaps, Nettelbeck (1982) concluded that this level of correlation was an overestimate.

In 1987 Nettelbeck published a major conceptual review of IT research and conducted a semi-quantitative analysis of the IT–IQ correlation. Including only those sixteen studies which tested young, non-retarded adults (a total of 439 subjects), the average uncorrected correlation between IQ and IT was -0.35 . Many studies tested only undergraduates and Nettelbeck estimated the true correlation to be about -0.5 . He suggested also that the association between IT and Performance IQ might be stronger than that between IT and Verbal IQ.

Kranzler & Jensen (1989) conducted a formal meta-analysis of IT–IQ studies. They included published and unpublished work, but excluded studies with handicapped subjects. They found 31 acceptable studies (1120 subjects). The estimated corrected correlation between IT and IQ was -0.5 . The average uncorrected correlation between IT and Performance IQ was -0.45 , whereas that with Verbal IQ was only -0.18 . Similarly, Deary (1993) tested 87 non-neurologically impaired young adults with diabetes and found that the correlation between IT and Wechsler Revised Performance IQ was -0.42 , whereas the correlation with Wechsler Verbal IQ was -0.19 . This latter sample had a standard deviation of 13 IQ points. Studies appearing since the Kranzler & Jensen (1989) meta-analysis are consistent in supporting the finding of a moderately sized correlation between psychometric intelligence and IT (Juhel, 1991; Zhang, 1991; Bates & Eysenck, 1993; Chaiken, 1993; Chaiken & Young, 1993; Deary, 1993; Evans & Nettelbeck, 1993; Egan, 1994; Nettelbeck & Rabbitt, 1992; Deary *et al.*, 1991).

Therefore, unlike its antecedents, IT has been established by diverse researchers as a moderately strong correlate of psychometric intelligence. The effect has been widely replicated in different laboratories and in different countries, and there is a general consensus about the size of the effect. More research that merely replicates the association is unnecessary. What is needed hereafter is research that explains the IT–IQ correlation.

Explaining the association

Settling down to normal science

As soon as correlations appeared between IT and psychometric intelligence, a two-headed controversy emerged. First, there were doubts about whether the association existed in the general population at all, given the small and non-representative samples included in the original studies (Howe, 1988; Lubin & Fernandez, 1986; Vernon, 1986; Mackintosh, 1981; Nettelbeck, 1982). As late as 1988, Howe wrote that:

‘When the methodological defects have been remedied and representative samples used, the magnitudes of the observed correlations [between inspection time and psychometric intelligence] reduce considerably, typically to around -0.3 or less . . . or to zero.’ (Howe, 1988).

Such doubts have now been answered definitively. The correlation between IT and psychometric intelligence is modest and very robust; IT can account for a substantial minority of the variance in psychometric intelligence, but not as much as was thought in the very early stages of the research.

The second area of controversy was the reason for the correlation. Explanations tended to be delivered from the armchair. That is, having accepted the correlation as established, pundits attempted to explain the correlation in intuitive terms. To put it simply, there were two views of the reason for the correlation. First, some viewed the

Table 1. Comments on the nature of inspection time (IT) or the reasons for the IT–mental ability test score correlations

Author	Comment
Reductionist	
Vickers <i>et al.</i> (1972)	'the average time needed to make one momentary inspection of the sensory input'
Nettelbeck (1987)	'an index of the <i>efficiency</i> of the activity associated with early central stages of perception rather than as speed of apprehension'
Brand & Deary (1982)	'speed of intake of the most elementary information'
Bates & Eysenck (1993)	'[speed of] processing of retinal signals into a short term store'
Stough <i>et al.</i> (1995)	'perceptual speed'
Non-reductionist	
Irwin (1984)	'It may be that more intelligent children were able to master the requirements of the task more quickly than the less intelligent, or to approach the task with less anxiety because of their general success at problem-solving, so that the slight correlations found stem from these effects'
Mackintosh (1986)	'[with regard to IQ-evoked potential correlations] one might want to attribute uniformity across trials to factors such as willingness to comply with instructions or ability to maintain concentration on a remarkably tedious task. . . . similar factors may underlie the correlation between IQ and both inspection times and reaction time'
Howe (1988)	'Even with very simple tasks that involve highly familiar materials it is more than likely that performance at them is affected by experience-induced differences in (for instance) motivation, confidence, and attentiveness, any of which, alone or in combination, could account for the observed correlations'
Ceci (1990)	'the more elaborately one represents a stimulus, the faster it can be recognised. If encoding were a straightforward measure of CNS efficiency, then why should knowledge-base effects such as these exist?'

correlation as evidence that IT assessed a low level perceptual–cognitive function that was basic and partly causal to individual differences in intelligence. Second, some took the view that variance in IT performance was a high level artefact of intelligence; that is, bright individuals found ways to perform well in the IT task because of high level cognitive abilities. Table 1 shows various comments which indicate the variety of opinions on the nature of IT and the reason for the correlation between IT and psychometric intelligence.

To illustrate the distance that may separate various interpretations of the nature of IT, consider first the comment from Vickers & Smith (1986),

'One major strategy guiding attempts to measure the speed of mental functioning has been to isolate some process sufficiently elementary to be relatively immune from

influence by higher cognitive activities or by motivational and social factors. In its focus on a simple, component process, likely to play a limiting role in most (if not all) more complex processes, this strategy resembles the employment of standard algorithms as benchmark tests of the processing speed of a digital computer. In the field of human information-processing research, it has been argued, an analogous measure of speed is provided by an inspection time (IT) index, first proposed by Vickers *et al.* (1972), and defined as the time required by a S to make a single observation or inspection of the sensory input on which a discrimination of relative magnitude is based.'

Compare this with Howe's (1988) assessment of the research which demonstrates a modest correlation between IT and psychometric intelligence,

'However simple and familiar the tasks, it is unlikely that the qualities they draw upon are "basic" to the extent that the observed small correlations between performance at them and global measures of ability must reflect inherent mental processes rather than ones that are, at least in part, products of individuals' particular experiences. In short, there are no firm grounds for believing that there exist fundamental differences between individuals in the basic cognitive processes that underlie intelligent behaviour.'

This controversy contains two important questions about the now-established IT-IQ association: first, what is the direction of causation between the two variables (is IT a cause or a consequence of IQ differences?); and second, what is the mental/psychophysiological construct(s) being assessed by IT (does the original rationale for IT still hold?). The answers to these questions are unlikely to arrive quickly. Whereas the process of establishing the correlation has been relatively quick and definitive, its understanding entails research in areas that are foreign to differential psychologists, such as psychophysiology, psychophysics, experimental psychology and developmental psychology. Therefore, it is encouraging that there now appears to be a critical mass of researchers interested in IT. It would be easy for interest to decline after the exciting phase of discovery. The present phase is one of normal science, where many leads and hypotheses are being explored to explain the IT-IQ association.

The nature of IT

Evoked potentials

Zhang, Caryl & Deary (1989a) argued that opinions about the stages of information processing measured by IT were vague and contradictory, and that correlation studies were unlikely to throw much light on this important issue. They proposed that studies of the brain's averaged evoked potentials (AEPs) in response to the IT stimulus might throw light on the mental processes involved in IT task performance. In such an approach one has three variables whose correlations must be understood: mental test scores, IT ability, and AEPs. Whereas such an approach can help the process of reductionism, it remains to be shown that any association between IT and AEPs is the part of the IT variance that is shared with IQ-type measures.

Zhang *et al.* (1989a) collected event-related potentials (ERPs) from sixteen subjects while they performed the IT task; that is, the ERPs were evoked by the IT stimuli, not by standard stimuli such as auditory tones. They found a significant correlation ($r=0.44$, $p<0.05$) between IT performance and the brevity of so-called P200_T, which

was defined as the 'time measure measured from the point at which the upward slope of the N150-P200 complex intersected with the mean potential to the place where the P200 peak occurred'. (In this nomenclature N and P refer to negative and positive electrical potentials, respectively, and the numbers indicate, in msec, the time after stimulus onset at which the particular waves appear.) Correlation of IT with P200 latency was similar, though non-significant, and the correlation between IT and P300 somewhat lower. The authors suggested that, given the available literature on P200, the results were compatible with a view of IT performance which associated it with the process of encoding information from the sensory register to working memory.

In a further article, Zhang, Caryl & Deary (1989b) included IQ-type measures in addition to IT and AEPs. They reasoned that, because various authors had suggested that IT ability might involve attention, encoding from sensory to short term memory and/or decision making processes, and because all of these processes were studied using AEPs, AEPs might throw light on the processes being assessed in an IT task. In addition, an assessment might be made of whether such processes related to the IT-IQ correlation. In their first and second experiments the authors replicated the significant correlation between IT ability and $P200_T$, and found that, whereas this measure was insensitive to the difficulty (duration) of the IT stimulus, the P300 amplitude was sensitive, with more confident judgements associated with higher amplitudes. There were no significant correlations between contingent negative variation measures and IT performance, which suggested that post-stimulus processing, and not preparation for the stimulus, was important in the IT task. Finally, the $P200_T$ evoked by an unsped stimulus was related to Alice Heim 5 scores but the $P200_T$ evoked by a standard IT stimulus was not. In general, the authors concluded that the incomplete literature on the nature of P200 was congruent with the notion that IT was partly indexing the speed of some decision processes made on sensory information as it is passed to short term memory.

Citing a desire to confirm the particular aspects of stimulus evaluation time that IT assesses as their major motivation, Colet, Piera & Pueyo (1993) conducted further research on IT and AEPs. They tested 200 subjects on an auditory oddball task and separately took IT measurements. Therefore, in their study, IT performance was to be correlated with AEP latencies and amplitudes collected from a standard AEP procedure. The correlation between IT performance and $P200_T$ in the two evoked potential channels was 0.56 and 0.41. However, they also found correlations of 0.36 and 0.40 between IT and P300 latencies in the two channels. It is important to note that, in this study, the AEPs were collected to auditory stimuli and that the IT was a visual task. The IT and $P200_T$ variables were both associated with 'stimulus evaluation time' in the opinion of the authors, whereas P300 was related to 'context updating speed'.

Further research in this vein was conducted by Morris & Alcorn (1995) to investigate the similarity between the putative processes measured by IT ('the speed with which information in the sensory register is transferred to short term memory') and P200 ('a marker of the transfer of information to STM'). Instead of the $P200_T$ they measured the slope of the P200. They collected AEPs to briefly presented letters which were replaced by a backward mask at stimulus offset; this is comparable with Zhang *et al.*'s (1989a,b) procedure of collecting AEPs to IT stimuli. The 49 subjects were also given Raven's progressive matrices (RPM). The RPM scores and letter recognition

accuracy correlated at about -0.4 . Nine out of twelve correlations between RPM and P200 slope were significant in the frontal and temporo-occipital areas (mean $r=0.37$), but none of those in the temporal and occipital sites was significant. Whereas RPM correlated significantly with P200 slope, it had no significant association with conventional N100 and P200 latency measures. There were modest but significant correlations between recognition accuracy scores at the briefest duration and P200 slope in the frontal and temporo-occipital areas (mean $r=0.30$). This report, therefore, shows universally significant correlations among P200 slope, an IT type measure and IQ-type test scores.

Caryl (1994) also developed a P200 gradient measure and, in a study where AEPs were collected in response to IT stimuli, the P200 gradient showed peak correlations (at about $0.4-0.5$) with IT and Heim 5 scores at about 150 msec after stimulus onset. In terms of the mental processes that are important for good performance on the IT task, Caryl commented that 'lapses in preparation for the IT discrimination were unimportant in accounting for differences in IT . . . IT-related differences in ERPs can be found between 100 to 200 ms.' Caryl's discussion of the psychological processes that take place during the 100–200 msec post-stimulus epoch includes mention of stimulus analysis and identification, a note to the effect that this is an epoch during which there is competition for competing resources if more than one task is underway, and that this is an epoch during which attention influences the ERP waveshape. He makes a suggestion about the key ability tapped by IT and the proper direction for future research:

'Perhaps ability to focus attention is the fundamental difference between individuals in this task rather than a difference in speed of perceptual intake. Productive debate about the precise nature of the mechanism involved should be possible once the critical epoch has been identified (e.g., as 100–200 ms) and the aspects of stimulus analysis occurring in this epoch have been established.' (Caryl, 1994).

This one area of research on IT shows both progress and remaining problems. Like the association between IQ and IT, the association between IT and an aspect of the P200 wavefront has been replicated. There is some evidence to indicate that this aspect of the brain's response to a stimulus might be linked to superior performance on the IT and IQ-type tasks. A handy cognitive epithet for IT remains elusive, as does a clear account of the brain processes involved. However, there are congruences between IT and P200 with respect to some opinions of what these measures represent: some aspect of time-dependent stimulus analysis and information accumulation has been suggested in both.

Psychophysics

Part of the attraction of IT, once it was found to correlate with mental ability test scores, was its theoretical rationale, which gave the task a tractable basis in terms of visual processing and decision making theory. After a critical examination of some aspects of IT, Anderson (1992) was still moved to say that 'IT is very much a *psychophysical* task. That is, it is a task that has well-defined psychophysical functions and whose main parameters are influenced by sensory/perceptual variables, rather than by cognitive ones'.

In fact, although there has now been much work on the individual differences

associated with inspection times, the psychophysical study of IT has lagged behind. For many years, while research on individual differences was demonstrating a clear and substantial correlation between IT and psychometric intelligence, the psychophysical basis of inspection time went largely unquestioned: Vickers' original view that the parameter being measured was the speed of a periodic inspection process was tacitly accepted and frequently repeated in the introductions of articles on the IT-IQ association. However, the original rationale for the IT is now being questioned and additional parameters relevant to IT performance are being entertained. The three most thorough re-evaluations of the theoretical aspects of IT have been by Vickers & Smith (1986), Levy (1992) and White (1993).

Levy (1992) found some aspects of the theory of IT mathematically intractable, stated that some aspects of Vickers' theory were intuitive rather than explicit, and thought that a number of alternative models of the processes underlying inspection time remained to be tested. He further commented that the development of a statistical model of IT performance whose parameters refer to statistically accessible factors will require very large amounts of data from single subjects. Such research is more in the tradition of psychophysics than individual differences; in the latter type of research the emphasis is on the numbers of subjects and relatively small amounts of data tend to be collected from each subject.

Levy's challenge to the IT model which includes only a single parameter in performance differences has been taken up by various researchers. Chaiken (1993) examined models of IT that include processing distraction and memory strength in addition to processing speed. His findings suggest that more than a single process is being measured in the IT procedure. Smith (1992) found effects of an item's information content in addition to exposure duration on the probability of correct discrimination. Muise *et al.* (1991) conducted experiments that potentially overturned a key aspect of Vickers' model. They hypothesised that in processing information in brief displays there is a two-stage process. First, there is a duration (T_{Lag}) over which no useful information may be extracted; this might be seen as sensory inertia. Thereafter, the probability of correct discrimination increased in a manner that was described by a negatively accelerated exponential function. The idea of an initial stimulation duration over which no useful information may be collected was also raised by Levy (1992).

Data relevant to some of the issues raised above were collected by Deary, Caryl & Gibson (1993). They conducted extensive testing on two subjects until each had undertaken 38,400 trials in 60 sessions over about 3 months. The shape of the curve between stimulus duration and response probability was clearly described by a normal ogive, the first time this had been established in large scale testing. Also in support of Vickers' model was the absence of any evidence for a T_{Lag} ; the subjects were scoring at above chance levels when durations were as brief as a few milliseconds. However, more worrying for models of IT function was the evidence found for non-stationarity. Moreover, each of the two subjects showed evidence of different types of non-stationarity. One subject showed very high stability at durations over 10 msec. However, below this level he showed improvements in some durations but worsenings in durations only 1 msec apart. Speculatively, this was thought to be related to high level 'tuning' of IT performance whereby an attempt to improve one aspect of

performance upset another facet. The other subject tested by Deary *et al.* (1993) showed very long term improvements, but no declines, in the 13–20 msec region. Stationarity is a very basic assumption of all IT models and, if these findings prove replicable, future models will have to incorporate the temporal dynamics of IT performance.

White's (1993) critique of IT research includes a reminder that an essential aspect of IT is backward masking and that, as such, researchers in IT must become more aware of relevant theories of visual perception. White argues that IT is not, as Vickers' model assumed, a post-sensory cognitive phenomenon; instead, White views IT as sensory. Certainly, White's view that there are many relevant programmes of perceptual research to which IT devotees might usefully turn is correct. For example, Bergen & Julesz (1983) conducted a series of experiments on a phenomenon they called 'inspection time', even though it was clear that they had no awareness of the IT research referred to in this paper. Using a backward masking procedure, they examined the stimulus duration that was necessary for subjects to identify the presence or absence of a vertical target line in an array of differently oriented lines. The stimulus onset asynchrony needed to spot the vertical lines when the other lines were at 90° was 60 msec; this rose to 200 msec when the other lines were only 20° different from the target line. In fact, these researchers identified parameters akin to the 'inspection time' and 'noise' found by Vickers *et al.* (1972).

The problems of IT's original psychophysical rationale do not detract from the IT–psychometric intelligence correlation. However, the problems indicate the need for caution before assuming that the construct that links the two variables is understood. There is much expertise in the area of visual backward masking that is ignored by IT researchers and must now be considered relevant. Some procedures related to IT not only have more attention paid to them by psychophysicists but also have some putative biological bases. For instance, the sustained and transient channels in visual perception, which are thought to deal with fast, low contrast and slow, high contrast information, respectively, are thought to be based on the parvocellular and magnocellular pathways in the visual system (Breitmeyer, 1980; Lovegrove, 1994; Miles, 1994). Moreover, the research on appearance and disappearance in visual fields is highly relevant to IT research and has a link to activity in the lateral geniculate nucleus of the brain (Phillips & Singer, 1974; Singer & Phillips, 1974).

Researchers on IT must become aware of the wider psychophysical research that addresses the early stages of visual processing, as well as IT's questionable theoretical basis and limited empirical evidence. An alliance between differential psychology and perception research is needed fully to understand the nature of the between subject differences in IT and the construct that links IT to higher level mental abilities.

Non-reductionist approaches

Attempting to find shared biological correlates of IT and psychometric intelligence, and searching for the key psychophysical parameters of IT performance (and perhaps even their biological bases) follows a traditional reductionist assumption that IT is a lower level task than IQ-type test items. However, as already mentioned, there are some who have viewed IT performance as the result of higher level abilities. That is, far from

IT being a low-level element of IQ, some suggest that a good IT is the result of being clever. This line of argument has various strands.

Strategies. One attempt to explain the IT–IQ correlation in terms of higher order processes was to state that bright subjects have better IT performance because they use high level cognitive strategies to solve the IT task items. One such strategy, afforded by some versions of the IT task more than others, is to look for an apparent movement artefact between the IT stimulus and the mask that follows it. However, contrary to the strategy hypothesis, the IT–IQ correlation is lowered rather than caused by strategy use; that is, the expected IT–IQ correlation is found among non-strategy users and not among the users of strategies (Mackenzie & Bingham, 1985; Mackenzie & Cumming, 1986). In a large study, Chaiken & Young (1993) found a correlation of -0.35 between IT and Cattell Culture Fair test scores; the correlation among the subgroup of strategy users was -0.21 (ns) and among the non-strategy users was 0.56 ($p < 0.01$). Others have found no effects of strategies on the IT–IQ correlation (Egan, 1994). One study reported similar correlations between IQ-type test scores and IT estimates made with various IT masking procedures, some of which afford strategies and some not (Stough *et al.*, 1996a). No studies to date have suggested that the use of strategies accounts for the association, though strategy theories are notoriously difficult to operationalise as testable hypotheses (Brand, 1987). Moreover, there have been considerable improvements in masking procedures designed to eliminate stimulus-mask artefacts in the IT task (Knibb, 1992; Evans & Nettelbeck, 1993; Sadler & Deary, 1996).

Motivation and personality. The possibility that a non-intellective variable such as personality and/or temperament might be the key aspect of IT performance that brings about the IT–IQ correlation was posited by Howe (1990). This was tested by Stough *et al.* (1996b) in 68 subjects who were given the Wechsler Adult Intelligence Scale, Raven's Advanced Progressive Matrices, IT, the Eysenck Personality Questionnaire and the Strelau Temperament Inventory. In accordance with other studies, they found a correlation of -0.44 between IT and performance IQ. Partial correlations, removing the effects of personality and temperament, were negligibly different from the raw correlations, leading the authors to conclude that these variables do not mediate the IT–IQ association.

The effect of motivation on the performance of IT and its effect on the IT–IQ correlation was studied by Larson, Saccuzzo & Brown (1994). They tested over 100 college students under conditions of incentive and no incentive. In addition, effort expended on the task was assessed with physiological and self-report measures. They found that there was no difference in the IT–IQ correlation between groups who did and did not receive incentives to perform well; subjects in the incentive condition were told that they would receive up to \$20 if they improved their scores over their first visit to the laboratory. The authors concluded that motivational differences were not responsible for individual differences in IT tests. They suggest two reasons for this. First, they suggest that subjects on the whole are well motivated in the laboratory. Second, the IT task is so simple that additional motivation does not improve an individual's score. They conclude that:

'The correlation between IQ and performance [on inspection time and other laboratory tasks] for experimentally motivated subjects is just as strong as it is for random groups.

Clearly, then, the information processing/intelligence correlations found here and in previous studies cannot be attributed to motivation alone. Some other process such as some basic underlying aspect of intelligence is needed to account for the well documented IQ-Performance correlation.' (Larson *et al.*, 1994).

Generality of correlations (learning and novelty). It is possible that the IT-IQ correlation might be explained by the fact that brighter individuals perform better on any novel task, and simply learn more quickly the procedural requirements of a task. Evidence supporting such an hypothesis was provided by Nettelbeck & Vita (1992). They tested groups of 5-6-year-olds and 11-12-year-olds on Raven's Coloured Progressive Matrices and repeated estimations of inspection time. They found that initial IQ-IT correlations in the region of -0.5 eventually dropped to near zero levels. However, they also found that, eventually, most subjects altered the way they performed the task; by the end most subjects were using post-stimulus apparent movement cues, which tend to decrease or eliminate the IT-IQ correlation.

By contrast with Nettelbeck & Vita's (1992) results Chaiken (1993) found that the IT correlation with Cattell Culture Fair scores was higher (0.50) at the second testing of IT than at the first (0.35). Chaiken concluded that the validity of IT increases with practice and the mechanism of this might be that practice on the IT task eliminates the use of the apparent movement strategy.

Raz *et al.* (1987) tested the notion that high IQ subjects performed well on IT-type tasks because they perform well on any novel task. However, their evidence suggested that it was only psychophysical tasks that demanded discriminations under time-limited conditions that correlated significantly with IQ test scores. A difficult detection task—detecting the presence or absence of a sound between bursts of noise—showed individual differences but these were not correlated with IQ. Results from the author's laboratory (unpublished) have correlated individual differences in the ability to detect the appearance of a small square in an array of 49 identical squares, a task first used by Phillips & Singer (1974). The time between the onset of the 49 squares on the viewing screen and the appearance of the new square varies from 14 to 140 msec. The correlation between scores on this visual change task and Alice Heim 4 scores was 0.43 ($n=65$, $p<0.001$). The correlation between IT and Alice Heim scores was 0.4, and between IT and visual change detection was 0.35. However, measures of visual contrast sensitivity correlated at near zero levels with all three tasks. Therefore, this tends to suggest that it is the element of speeded presentation of stimuli that is necessary for the correlation. The notion that performance on any novel task will correlate with IQ scores is false.

Direction of causation. A general claim made by the non-reductionist, that covers all of the hypotheses in this section, is that IQ differences cause IT. This possibility was examined by Nettelbeck & Young (1990) who tested 30 7-year-old children on two occasions, about a year apart, on visual IT and on the Wechsler intelligence scale for children. Because both measures had been taken twice, Nettelbeck & Young used the method of cross-lagged correlation to estimate which of the variables had causal precedence. The theory of the cross-lagged panel states that whichever variable at time 1 has the stronger correlation with the other variable at time 2 is likely to be causal. In fact, Nettelbeck & Young (1990) found that the cross-lagged correlations were equal

(both 0.4) and concluded that some other factor might cause individual differences in both IT and IQ. In fact, their conclusions were erroneous, because the stabilities of the IQ and IT measures across time were very different. Deary (1995) replicated this design using over 100 children at 11 and 13 years who were tested on an auditory IT test and on Raven's Matrices and the Mill Hill Vocabulary test. After testing various causal hypotheses by applying structural equation modelling to the correlations, he found some evidence that the processing abilities measured in the auditory task contributed to later intelligence differences, but not the reverse.

Conclusion

The quest for the basic processes underlying intelligence has never been more hopeful. In the past, interesting findings were not developed into a theory of intelligence and its causal bases, having failed to attract sufficient interest among psychologists (Deary, 1986). Some of the initial overstatement and controversy that attended the early IT-IQ studies (Brand & Deary, 1982; Mackintosh, 1981; Nettelbeck, 1982) has had welcome effects. The high profile IT was given generated sufficient interest to allow many replications of the IT-IQ correlations, even in the laboratories of the sceptical (Longstreth *et al.*, 1986). The interest shown then has firmly established the moderately strong association that exists between IT and psychometric intelligence. However, the long task of explaining the correlation has only begun. This paper has highlighted some areas of research—psychophysiology, psychophysics and non-reductionist approaches—and could have discussed others such as development (Nettelbeck & Vita, 1992; Nettelbeck & Young, 1990; Nettelbeck & Wilson, 1985; McCall, 1994), psychopharmacology (Stough *et al.*, 1995; Deary, 1992; Petrie & Deary, 1989), neuropsychology (Nicholls & Cooper, 1991; Sadler & Deary, 1996) and auditory research (Deary, 1994; Raz *et al.*, 1987). Though this research is diverse, it is necessary that some periodic integrative reviews are undertaken to monitor its progress. Understanding IT and the IT-IQ association will contribute towards an understanding of a substantial minority of the variance in human intelligence.

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