Inspection time and cognitive abilities: An event-related potential study

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Summary

This research has been concerned with the nature of the relationship between performance on a simple backward pattern masking task and higher cognitive abilities. The pattern backward masking task 'inspection time' (IT) is known to share about 25 per cent of variance with performance IQ scores from the Wechsler scales. Similar results have been found with scores on Raven's matrices. The relationship is: the shorter the IT, the higher the IQ score. The method chosen to investigate this relationship was the cortical event-related potential (ERP), a measure derived from the scalp-recorded electroencephalogram. The ERP is an estimate of the cortical activity associated with some particular physical or cognitive event. A feature of the ERP relevant to this study is its fine temporal resolution of information processing within the cortex. This feature offers the potential for identifying processes common to IT and to higher cognitive processing.

This thesis has eight chapters. Chapter 1 provides an introduction to IT and to the relationship of IT with IQ. Also in Chapter 1 is an introduction to the ERP methodology. This is followed by a discussion of Robinson's (1993) arguments about some confusion in the ERP literature on IQ arising from misunderstandings on the importance of reference electrode placement. Finally, there are preliminary remarks on ERP work concerned with IQ, or IT, or both.

Chapter 2 reviews the theoretical bases of the Hendrickson 'string measure' (Hendrickson & Hendrickson, 1980; D.E. Hendrickson, 1982). This measure derives from a model of intelligence that holds that rate of errors in neural transmission forms the basis for individual differences in intelligence. This review discounts the theoretical bases of the string measure. Consideration of empirical research that has used the string measure has identified two competing theories about the directions of correlations between the string measure, IT, and IQ test score. The first is the Hendricksons' theory, which predicts positive correlations

between the string measure and IQ (and therefore negative correlations between the string measure and IT). The second theory is that of Bates (Bates & Eysenck, 1993; Bates, Stough, Mangan & Pellett, 1995); this theory predicts that the direction of correlation depends on the attentional demands embedded in the experimental procedure. If the procedure has no attentional requirement, then the theory makes the same predictions as the Hendrickson theory. However, if a demand for focussed attention is made, the direction of correlation is reversed.

Chapter 3 reports an experimental test of these competing theories. This used an experimental procedure similar to that used by Bates and Eysenck (1993), in that it obtained ERPs as IT was undertaken. Forty subjects completed IT estimation, IQ testing and ERP recording. Correlations between the string measure and IQ were near-zero. To the extent that support for either the Hendricksons' theory or Bates' theory could be claimed, some part of these results were consistent with the Hendricksons' theory. Chapter 3 concludes with a discussion on how the string measure relates to the ERP—that is, what does the string measure actually measure?

Chapter 4 presents a model that was developed to account for the pattern of relationships reported in the literature between the string measure and IQ test scores. This model proposes that the string measure is nonspecific in that it indexes any and all features of the ERP; but that it is particularly sensitive to amplitude differences and to high frequency event-related activity. This model generated hypotheses that were tested using Fourier analyses of the event-related potentials recorded in the experiment described in Chapter 3. The model postulates that the string measure incorporates both low- and high-frequency event-related activity. This prediction was confirmed by a series of correlational and multiple regression analyses. The string measure was found to be nonspecific and therefore not useful for understanding the relationship between information processing in the cortex and IT and intelligence. It was concluded that this measure should be abandoned.

Chapter 5 begins with an examination of the relationship between IT and IQ. It is argued that an approach that describes cognitive abilities in terms of several general or broad factors, rather than in terms of a single general factor, may yield a better understanding of IT and its relationship with IQ. An operationalisation of Horn and Cattell's model of cognitive ability, commonly known as Gf–Gc theory (for general fluid and general crystallised ability), was examined and adopted for use in the remainder of the thesis. The chapter then concludes with a comprehensive review on the literature on IT and ERPs. It is argued that a general model relating brain function to ERPs may explain previous findings. Also arising from this chapter, and presented as Appendix III, is an experimental test of Caryl and Harper's (1996) caution against recording ERPs during IT estimation via adaptive staircase procedures. Caryl and Harper argued that confounding task threshold and task difficulty may result in differences in ERPs in a latency band crucial for understanding relationships with IT and IQ. In the experiment described in Appendix III, trials were presented at three target durations. These three types of trials were either: very easy; or very difficult; or of an intermediate level of difficulty such that about 75 per cent of trials were correctly discriminated. The critical comparison involved trials correctly discriminated, or not, at the intermediate level of difficulty. There were no differences in the ERPs. It was concluded that ERPs can be recorded during IT estimation by an adaptive staircase method, if trials with very long durations (i.e., easily discriminated trials) are excluded from averaging.

Chapter 6 develops a general model relating an aspect of brain efficiency to cognitive abilities. This new model defines efficient cortical information processing in terms of the rise times of short latency components within the ERP. This definition arose from the observation that the firing of a neuron within the central nervous system depends on the integration of converging inputs from other neurons. The rate at which converging inputs on the neuron cumulate their activity to raise nett membrane potentials to the threshold firing levels therefore may reflect a design feature of individual brains that may relate to functional efficiency. Specifically, more concentrated recruitment would lead to earlier and more reliable firing in each station in a neuronal circuit and thus to faster, more reliable activity in the circuit overall. Because, as is generally accepted, gross electrical records at the scalp reflect postsynaptic fields, then the viewpoint taken here is that the rise times of ERPs reflect recruitment and, indirectly, brain efficiency. The advantage of using such a measure is that it is concerned with the earliest response of the sensory cortex. That is, it is a measure of a low level characteristic of cortical response that may also underlie efficiency of higher functions within the cortex.

Chapter 7 describes an empirical test of the model described in Chapter 6. Sixty-four subjects completed IT estimation, psychometric testing and ERP recording. Some support for the model was found in that the rise times of short latency ERP deflections correlated significantly with IT and with a test of general speed of processing. However, it was found that ERP latencies were more highly correlated than rise times with psychometric measures. At occipital recording sites the relationships were predominantly with measures of processing speed (including IT) and short-term memory. At a non-occipital site, the longer latency deflections had moderately high correlations (up to $-.54$, $p < .001$) with tests of fluid and crystallised ability. This pattern of relationships was interpreted as consistent with the information processing hierarchy thought to underlie the model described by Gf–Gc theory. A final issue addressed was whether, as commonly assumed on the basis of previous findings, IT correlates with fluid ability. IT did not correlate with fluid ability but correlated significantly ($-.42$, $p < .001$) with a test of speed of processing. Partial correlations and factor analyses suggested that the relationship of IT with a higher-order general factor depends on shared variance with measures of speed of processing.

Chapter 8 presents a summary of the thesis and discusses prospects for future research. It is suggested that IT is best understood as one of a family of pattern backward masking tasks that are likely to define a lower-order factor contributing to a broad general speed of processing factor. Research using high resolution EEG and a procedure similar to that used in Appendix III should provide evidence on the processing involved in completion of the IT task.

Statement

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University and to the best of my knowledge and belief contains no material previously published or written by any other person except where due reference is made in the text of the thesis.

If accepted for the award of the degree for which it is submitted, I consent to the thesis being made available for photocopying and loan.

Nicholas R. Burns

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Chapter One: An introduction to IT and ERPs

1.1 Preamble

This thesis is concerned with the relationships between inspection time (IT) and cognitive abilities. The method chosen to investigate these relationships is the event-related potential (ERP), a measure derived from the scalp-recorded electroencephalogram (EEG). This concatenation of an information processing measure, psychometric measures, and physiological measures means that a complex set of relationships are set in juxtaposition. Of necessity, the IT measure and the relationships between IT and cognitive abilities will be described. The literature on the relationships between ERPs and cognitive abilities is also reviewed. The limited literature on the relationship between IT and ERPs is reviewed in detail. Finally, a discussion on models of cognitive abilities forms part of the development of the thesis.

1.2 Inspection Time

The view of IT taken here has been developed through a theoretical and experimental research program (Burns, Nettelbeck & White, 1998; White, 1993, 1996) that has led to a somewhat different interpretation of the measure and its relationship to cognitive abilities than was taken by the originators of the measure (Vickers, Nettelbeck & Willson, 1972; Vickers & Smith, 1986; Nettelbeck, 1987). The IT measure arose from a model of comparative judgement (Vickers, 1970). In its most common form the task involves the presentation of a target stimulus consisting of two vertical lines of markedly different length, joined at the top by a line. The target stimulus is followed by a patterned mask and the subject indicates on which side of the figure, left or right, the shorter (or longer) line appeared (see Figure 1.1). IT is therefore an estimate of threshold accuracy and most commonly has been defined as the stimulus onset asynchrony (SOA; i.e., duration between target onset and mask onset) at which the task is solved with very high accuracy.

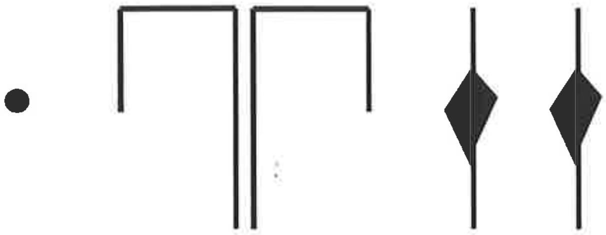

Figure 1.1. Warning cue (left), IT target figures (centre), and lightning mask (right) used in the experiments reported in this thesis.

The target in the IT task has often been referred to as a Pi figure (because the two lines are joined at the top by another line) and this term is adopted here. According to contemporary integration theory of pattern backward masking, the masking effect results from poor fine temporal resolution within the visual system (Coltheart & Arthur, 1972; Di Lollo, 1980; Eriksen, 1980; Eriksen & Schultz, 1978; Felsten & Wasserman, 1980; Sheerer, 1973). That is, at short SOAs the target and mask are temporally integrated and are therefore indistinguishable. At longer SOAs the features of the target and mask become distinguishable (Burns, Nettelbeck & White, 1998; White, 1996). This analysis of the task contrasts with the original rationale (Vickers et al., 1972; Vickers & Smith, 1986) wherein the lengths of the two lines were compared and evidence accumulated in quanta until a decision was reached. According to this perspective, the backward mask was employed to prevent sampling from the 'iconic store'.

The psychophysics of IT (and other pattern backward masking tasks) is interesting in and of itself. For example: Barrett, Petrides and Eysenck (in press) have examined the effect of applying various curve fitting procedures on obtained IT estimates; Burns, Nettelbeck and White (1998) tested various hypotheses on the nature of the task and the shape of the psychometric function associated with IT. These authors argued that resolution of some of these issues bears on the level of explanation for the relationship between IT and cognitive abilities; Deary, Caryl & Gibson (1993) explored the long-term stability (i.e., stationarity) of IT performance at a range of SOAs and found performance changed over time. They suggested that such issues must be addressed before parameterisation of the task can be meaningfully attempted. In other words, there are many issues concerning the IT task which must be fully explored before its relationship with cognitive abilities can be understood. This thesis will concentrate on the correlation between IT and cognitive abilities at the level of the temporal processing of information.

1.3 The relationship between IT and IQ

There is now considerable evidence for a moderate correlation of about –.5 between IT and IQ (Deary & Stough, 1996; Kranzler & Jensen, 1989; Nettelbeck, 1987), although whether IT relates to Spearman's *g* (e.g., Anderson, 1992; Brand & Deary, 1982) is uncertain. For example, evidence that IT correlates more with Performance IQ than with Verbal IQ from Wechsler scales (Deary, 1993; Nettelbeck, 1987; Nettelbeck, Edwards & Vreugdenhil, 1986) has been interpreted as specifically implicating fluid abilities. This claim (tested here in Chapter 7) assumes that the Wechsler scales capture fluid abilities and is controversial because of evidence that they do not (e.g., Carrol, 1993, p.702; Frank, 1983; Mc Grew, Werder & Woodcock, 1991; Woodcock, 1990). Correlations between IT and Raven's matrices (generally considered a good test of *g*) cannot provide unequivocal support for the proposition that IT relates to *g* because the matrices are generally administered under speeded conditions, that is, with a time limit imposed (see Carroll, 1993, pp.443-445) and to samples restricted in range on ability (see Kline, 1991, pp.55-56) and therefore the reported relationships may be confounded by relationships of IT with general speed of processing or with visuo-spatial abilities.

The initial interpretation of the relationship between IT and IQ implicated speed of some elementary cognitive function (Brand & Deary, 1982; Nettelbeck, 1987; Vickers et al., 1972). Recent research has supported a speed of processing interpretation (Deary, McCrimmon & Bradshaw, 1998) although there is evidence that, additionally, aspects of attention are involved (Bors, Stokes, Forrin & Hodder; in press; Hutton, Wilding & Hudson, 1998). A number of authors have also emphasised that, for a wide range of reasons, a moderate correlation between IT (or reaction time) and IQ does not establish mental speed as providing a sufficient explanation for intelligence (Mackintosh, 1981; Marr & Sternberg, 1987; Nettelbeck & Wilson, 1994; Stankov & Roberts, 1997; Wilson, Nettelbeck, Turnbull & Young, 1992).

It has been argued (or assumed) that ERPs are likely to be able to elucidate some of these issues (e.g., Barrett & Eysenck, 1992a; Caryl, 1994; Caryl & Harper, 1996; Deary & Caryl, 1993; Eysenck & Barrett, 1985; Hendrickson & Hendrickson, 1980; Zhang, 1987; Zhang, Caryl & Deary, 1989a, 1989b). This position rests on the fact that ERPs are time-locked to a stimulus (or response) and it should therefore be possible to make inferences on the timing of brain processing associated with the stimulus (Gevins & Cutillo, 1986, pp.336-337; Hillyard & Picton, 1987, pp.519-520). The position taken here is that ERPs are likely to be useful for elucidating the relationship between IT and IQ. However, interpretation of ERPs rests on assumptions sometimes not made explicit even in the specialist literature, let alone when ERPs are used by differential psychologists. Some of these assumptions are examined in the description of the ERP methodology that follows.

1.4 ERPs: An introduction to the methodology

Under ordinary conditions there is an ongoing stream of electrical (and magnetic) activity associated with the activity of the brain. Berger (Gloor, 1969) first reported the measurement of electrical activity via scalp electrodes in humans, the EEG. Adrian and Matthews (1934) confirmed the brain origin of these electrical signals. The EEG is taken to be the summation, temporally and spatially, of the post-synaptic potentials of synchronously activated neuronal populations, specifically the perpendicularly oriented (with respect to the cortical surface) pyramidal neurons (Azizi & Ogmen, 1993; Nunez, 1990; Regan, 1989). A corollary of this understanding is that much brain activity is invisible to electrodes placed on the scalp (Coles & Rugg, 1995, pp.4-5). Nevertheless, as Srinivasan and Nunez (1993) stated "it is widely appreciated that EEG is a direct measure, albeit often a crude measure, of conscious experience. Hundreds of distinct spatio-temporal patterns are now recognized and correlated with physiological, clinical and cognitive state" (p.311). The voltage of the EEG fluctuates with time over a range of about 100 μV and with frequencies of up to 40 Hz and higher.

An ERP is what the term itself says: it is a brain electrical potential associated with some sensory, motor or cognitive event. These potentials are typically much smaller in amplitude than the ongoing EEG and are, effectively, buried within the EEG. Ruchkin (1988) described the model of the ERP that is generally followed: "an ERP consists of the sum of an invariant signal and random noise ... the noise is assumed to be primarily due to activity generated in the brain that is not related to the event. Both signal and noise currents are volume conducted from their regions of origin to the vicinity of the recording electrode" (p.8). The ERP methodology relies on averaging of EEG, recorded in such a way that it relates systematically to the event of interest—that is, it is time locked to the event of interest. Given this model, then averaging of the time-locked EEG attenuates the noise signal in proportion to the square root of the number of EEG epochs averaged (Hillyard & Picton, 1987).

The status of these assumptions (i.e., of invariant signal and random noise) has been discussed by Regan (1989) and Ruchkin (1988). They pointed out that identical stimuli do not necessarily generate identical ERPs. Variability in latency, amplitude, or both, may arise from factors such as adaptation, inattention or fatigue, although experimental design may be able to control some of these factors to some extent. Similarly, the noise may not be statistically independent from the signal. Gevins and Cutillo (1986) put it this way: "the brain systems which generate event-related signals may not be different from those which produce ongoing EEG activity. It is possible that the task stimulus induces a reorganization of ongoing activity in a neural system as a subset of its population becomes engaged in event-related processing" (p.368). In the case of information processing tasks, subjects presumably actively seek solutions to problems and this may be reflected in changes in ongoing EEG activity from trial-to-trial. Consistent with this possibility, it has been suggested (e.g., John, Ruchkin & Vidal, 1978) that the ongoing EEG contains task-related information that is lost during the averaging process.

The methodology to be used in this thesis requires that the investigator weighs these issues. This applies when the work of others is considered but applies equally to one's own work.

Another aspect of the recording and interpretation of ERPs is now addressed, before turning to the more specific question of the application of this methodology to research into IQ and IT. This is the question of electrode placement and referencing during EEG recording. Although this may seem an especially technical issue to be introducing at this stage, it becomes of some importance in discussing one of the more controversial aspects of reported relationships between ERPs and IQ, that is, the suggestion by Robinson (1993) that inconsistencies in the literature have arisen because of misunderstandings on the outcomes of different recording procedures. For this reason it is best dealt with here.

When an electrode is attached to the scalp with the aim of recording the electrical activity emanating from the brain, a voltage is being recorded; that is, a difference in electrical potential between a recording electrode and the electrical potential at some other place. Logically, then, all electrode montages are bipolar. However, a differential classification is sometimes made between what are termed “monopolar” and “bipolar” montages. Monopolar recordings are those where the scalp electrode is referred to a (usually) non-scalp electrode; for example, when the recording electrode is referred to an electrode placed on a mastoid process or to an electrode attached to the tip of the nose or to an ear lobe. The point of this arrangement is that the reference electrode is assumed to be electrically neutral, or quiet, with respect to the brain. By this classification, the recording arrangement used here in Chapter 7—i.e., Oz referred to Cz of the International 10/20 system (Jasper, 1958, see also Figure 3.1 in this thesis)—is monopolar, even though both electrodes are placed on the scalp. This is because the reference site has been chosen because it is not influenced by the activity of interest (at least at the latencies of interest).

The bipolar category of recording is used when the interest lies in differences in electrical activity across the scalp; that is, between different regions of the brain. In this case, an electrode placed at one point on the scalp is referred to an electrode placed at another point on the scalp. Activity is therefore recorded at one site that is different to the activity at the other site. This category of bipolar recording can further be sub-divided as to the placement of the electrodes with respect to the mid-sagittal plane; if the electrodes are placed symmetrically with respect to the midline the recording montage is said to be bipolar symmetrical; an example would be electrodes placed at O1 and O2 (refer to Figure 3.1). A bipolar asymmetrical recording is any other bipolar placement (for example two electrodes 6 cm apart astride C4 and parallel to the midline (Ertl & Schaffer, 1969 [see below]).

The crux of the differentiation between monopolar and bipolar recordings, then, is that the former are records of all brain activity 'seen' at the recording site and the latter are recordings of differences in brain activity between recording sites. In practice, this means that monopolar recordings are of greater amplitude than bipolar recordings but may contain fewer components or peaks (Robinson, 1993). In pointing to the distinction between mono- and bipolar recordings as an explanation for inconsistencies in the ERP literature on relationships with IQ, Robinson explained that early reports of correlations between ERP latency and IQ were from bipolar recordings, but subsequent work, which failed to replicate these correlations, had used monopolar recordings. He went on to discuss the work of the Hendricksons (1981, see Chapter 2 of this thesis) and explained that they had applied their string measure to both types of recordings and found high correlations with IQ. Robinson interpreted this as an indication that the string measure indexes both the amplitude of an ERP and the higher frequency activity within the ERP (this possibility is addressed empirically in Chapter 4 of this thesis).

In summary, then, the foregoing discussion was very much aimed at the particular issue raised by Robinson (1993). The question of reference electrodes is a highly technical one (Regan, 1989) and Nunez (1990) remarked on this issue that "much time and energy have been lost over the years in EEG/ERP research as a result of misunderstanding of the physical principles underlying the recording and interpretation of potentials on the scalp" (p.27). One of the main issues raised in this thesis is that, if electrophysiological measures are to be used as a tool for understanding IT and cognitive abilities, they should be understood at their own level before they are related to constructs at the psychological level. In reading the literature, one sometimes suspects that, on the contrary, the physiological origins (and the interpretative complexities associated with these origins) are forgotten once the measures have been entered into a computer file.

1.5 ERPs and IQ: Preliminary remarks

The following is a survey of the ERP parameters that have been studied in relation to IQ. In the time domain, an ERP is a series of voltages as measured at the active electrode. That is, it is a waveform with deflections[1] that have latencies, measured from the event of interest. The latency of a deflection is defined by the point of maximum amplitude with respect to some baseline. Each deflection also has a polarity that is determined by the direction of the voltage recorded at the scalp electrode relative to the reference electrode. In the frequency domain, the data gathered in the time domain are submitted to a Fourier transformation; basically, this expresses the data as the sums of the amplitudes of sine waves at given frequencies (therefore this procedure is sometimes referred to as the spectral decomposition of the waveform).

Both the time and the frequency domain have been used in studies of the relationship of the ERP to IQ but the time domain has predominated, with only a handful of studies utilising Fourier analysis of the ERP. This is understandable because the great strength of the ERP methodology is its excellent temporal resolution (Regan, 1989), with latencies being measured with millisecond accuracy, or less. Indeed, as Giannitrapanni (1985) ponders "it is difficult to conceptualize physiologically ... findings of spectral analysis of evoked potentials because the spectral analysis methodology requires the removal of the data from the time domain while evoked potential data has characteristics which are different for each subsequent segment of time" (p.219). Despite this the Fourier analysis of ERPs has the advantage of

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[1] The term 'deflection' is used here to indicate that the voltage changes recorded at the scalp are a summation, temporally and spatially, of volume conducted activity. Here and elsewhere, the term 'peak' is used in the same sense. On the other hand, the term ERP 'component' is reserved for the activity arising from some neural generator(s) which may not be seen separately at the scalp.

being quantitatively tractable and is utilised here in relation to the Hendrickson string measure (D.E. Hendrickson, 1982; see Chapter 4). In the time domain, then, research initially focussed on the relationship between ERP latencies and IQ. This approach followed logically from a 'speed' hypothesis of individual differences in intelligence and predicts a negative correlation between peak latency and IQ. Some support for this hypothesis was found but results were inconsistent.

However, some studies also reported relationships between ERP amplitude and IQ. These findings have generally been serendipitous rather than theory driven. Some commentators have suggested, therefore, that an atheoretical approach to the search for ERP relationships with IQ should be adopted because this would provide a taxonomy of relationships which would inform theory development (Barrett & Eysenck, 1992a; Deary & Caryl, 1993). A vexatious problem was, and remains, the multifarious amplitude measures available and utilised. These are, in no particular order and using various authors' nomenclature: the absolute amplitude of a particular peak of interest, for example N1 or P200; the amplitude of a peak-to-peak excursion, for example N140-P200; the mean absolute amplitude of the ERP over the whole epoch or some temporal subset of the epoch; the area under a peak or peaks of interest; the oscillation of the ERP, which is a sum of amplitude differences; and the difference in amplitudes, or alternatively, the ratio of the amplitudes, of a peak or peaks between experimental conditions.

A particular and generally unaddressed problem (but see Robinson, 1993) with all but the last of these measures, the ratio of peak amplitudes between conditions, is that the amplitude measures may vary across recording sites, within individuals as well as between individuals, for reasons that obviously have no relationship with IQ. Some of these reasons are catalogued here.

First, the choice and relationship of the reference electrode to the recording electrode is crucial (Nunez, 1990). Second, the resistance at each electrode is critical in determining measured absolute amplitude. Generally, no account of this is taken and standard practice in electroencephalography requires only that electrode resistance is measured as being below some value, usually 5 kΩ. This is, of course, adequate for most research and clinical purposes (because correlations between absolute amplitude and other measures are not calculated) but highlights the danger inherent in utilising amplitude measures in establishing relationships between ERPs and IQ. Third, skull thickness (within an individual) can vary by a factor of three across the cranium (Todd, 1924). The skull is thinner over the temporal lobes, for instance, and this may account for higher EEG amplitudes often measured over this region (Nunez, 1990). Between individuals, the issue of skull thickness is even more pressing with there being a normal range of thicknesses extending from 1.5 mm to 9.5 mm (Oliver, 1969; Rogers, 1984). Given that the average electrical conductivity of the skull is two orders of magnitude less than that of brain tissue (Nunez, 1990), these differences will certainly affect potentials recorded at the scalp and these significant but unknown variations will, of course, confound absolute amplitude measurements.

This catalogue gives an indication of the difficulties of interpreting absolute amplitude measures of ERPs. It is also worth noting that the major ERP paradigms that utilise amplitude measures are based on amplitude differences or ratios within subjects. The issue of ERP amplitude measures assumes importance in Chapter 4 of this thesis which presents a theory on the relationship of the ERP string measure with IQ. A supplementary but important point is that the difficulty in quantifying ERP measures in a way that takes account of the biophysics involved in the genesis and recording of the signals actually acts to increase the likelihood of Type II error in any experiment that uses these measures.

Latency and amplitude, in all their varieties, then, are the two most obvious and commonly used parameters of the ERP that have been applied to research into IQ. As averred above, frequency domain analyses of ERPs have also been undertaken, but the most recent attempts in this regard are now 15 years old. So, it is the case, that until recently there seemed to be no way forward for ERP research into variation in IQ. But a new measure of the ERP appeared that, in two separate studies, accounted for half the variance in IQ scores. Indeed, its correlation with IQ approached the test-retest correlations of the IQ tests themselves. This measure, the Hendrickson string measure (A.E. Hendrickson, 1982: D.E. Hendrickson, 1982; Hendrickson & Hendrickson, 1980), is treated in detail in the next three chapters.

1.6 ERPs and IT: Preliminary remarks

As noted above, the notion that ERPs can elucidate brain processing of particular stimuli has been seen as likely to be useful in understanding the relationship between IT and IQ. This is because the estimation of an individual's IT involves repeated presentations of the IT stimuli—that is, the basic requirement for estimating the ERP by averaging the EEG is met. There is a small body of literature based on recording ERPs to IT stimuli and which relates conventional and novel parameters of the ERP to both IT and IQ (Alcorn & Morris, 1996; Bates & Eysenck, 1993; Caryl, 1994; Caryl & Harper, 1996; Caryl, Golding & Hall, 1995; Colet, Piera & Pueyo, 1993; Morris & Alcorn, 1995; Zhang et al., 1989a, 1989b). This literature is reviewed following Chapters 2 through 4 in which the Hendrickson string measure of the ERP is examined. It should be noted that there is an overlap, in that some remarkable correlations have been reported between IT and the string measure (Bates & Eysenck, 1993). It is for this reason that the Hendrickson string measure is addressed next.

Chapter Two: The Hendrickson string measure and related measures

2.1 History and theoretical bases

The theory from which the string measure of the ERP arose had its genesis in a theory of memory proposed by A.E. Hendrickson (1973). This theory will not be treated here since, more recently, the application of that theory to intelligence has received two treatments from its authors (Hendrickson & Hendrickson, 1980; A.E. Hendrickson, 1982) and, further, a detailed experimental study of the string and other EEG/ERP measures was reported at the same time (D.E. Hendrickson, 1982). In various places in both theoretical treatments the authors argued that their theory accounts for: memory; individual differences in 'biological' intelligence (both within and between species); sex differences in performance on standard intelligence tests as well as why females are underrepresented in the professions and as chess grandmasters; learning; instinct; the origin of the EEG and the meaning of the ERP in molecular terms; the relationship between inspection time and performance on standard tests of intelligence; and the origin of the phenomenon of the 'absent-minded professor'. Despite the explanatory power claimed by the authors of this theory, it has not been widely accepted, for reasons that are treated shortly.

There are several central postulates of the Hendricksons' theory, and these are as follows. The first postulate was concerned with how information is encoded within the nervous system and it specifically dealt with the encoding of incoming sensory information and its afferent progress. The suggestion was that action potentials, also called nerve impulses but invariably referred to by the Hendricksons as 'pulses', are encoded as 'pulse trains'. That is, the authors argued that temporally sequenced 'packets' of pulses are the means whereby information is encoded. Further, the temporal sequencing, or the specific time intervals between pulses, only take species-specific values; and to quote the authors, "we believe that certain neurons require constant or minimum numbers of pulses to be sent to them before they will logically respond." (Hendrickson & Hendrickson, 1980, p.5). The proposal for the existence of pulse trains arose because the Hendricksons objected to the notion of the encoding of information by the temporal and spatial summation of synaptic potentials during neuronal firing (Hendrickson & Hendrickson, 1980, p.4; A.E. Hendrickson, 1982, p.163). They argued that this notion implies a loss of information as the information travels afferently and they further argued that it runs counter to K.S. Lashley's doctrine of 'mass action' (e.g., Lashley, 1931).

Although any claim to understand how the brain processes information must be tempered by recognition of the overwhelming complexity of the brain, consultation of any standard neuroscience text (e.g., Kandell, Schwartz & Jessell, 1991) confirms the currently widely accepted theory that neuronal firing within the cortex depends on integration of post-synaptic potentials. As to the concept of 'mass action', this arises from demonstrations of the (lack of) effect of lesioning of the cortex on complex behaviours in the rat. However, Zeki (1993), for example, devoted large sections of his recent book to demonstrating some degree of localisation of function within the primate (including human) cortex and he showed how small lesions in specific areas of the visual cortex can produce myriad agnosias, achromatopsias and akinetopsias. The position taken here is therefore consistent with evidence regarding aphasias over a century old, which establishes some localisation of function within the cortex so that a literal interpretation of what Lashley meant by 'mass action' is not viable.

The next postulate of the Hendricksons' theory operated at the molecular level and centred on the molecules found, and on events which occur, post-synaptically. Their theory required that neurons can make selective responses to inputs (A.E. Hendrickson, 1982, p.163). These selective responses arise because "the neuronal firing centre has a number of sites which are associated with particular firing patterns that the neuron can send out in response to the appropriate incoming pattern" (A.E. Hendrickson, 1982, p.166). At the molecular level this is achieved (within the model) by two means. The first is the action of the neurotransmitter acetylcholine on the sodium-potassium pump. The second is the postulation of a type of ribonucleic acid (RNA) which they dub "engram RNA" and which encodes memories. In the model, the role of acetylcholine is to regulate the speed of the sodium-potassium pump at a structure of the post-synaptic membrane called the post-synaptic density. It is inside the post-synaptic density that engram RNA resides. The action of engram RNA involves recognition of an incoming nerve impulse and is dependent on the sodium concentration within the post-synaptic density, hence the role of acetylcholine in regulating the sodium-potassium pump. At this point it must be stated that all of this is highly speculative. The point of reviewing the theory is to demonstrate how the theory is linked to 'biological' intelligence and thence to ERPs.

The Hendricksons' theory proposed that 'biological' intelligence depends on the efficacy of the proposed recognition process. This in turn, depends on the action of engram RNA, which depends on the action of acetylcholine on the sodium-potassium pump, as outlined above. The suggestion is that information processing occurs via 'chains' of pulse trains; each link of the chain involves the processes outlined above. The requirement of the theory is that the chain of pulse trains has a logical outcome—that is, recognition of the last pulse train in the chain. However, the theory had nothing to say about the process by which this is achieved, although presumably recognition is the responsibility of some metacomponential executive process, such as Sternberg (1985) invokes. The Hendricksons' argued that what differentiates individuals on the dimension of 'biological' intelligence is the probability that acetylcholine 'correctly' regulates the egress of sodium from the post-synaptic density, thereby ensuring the 'correct' functioning of engram RNA, and hence the fidelity of information processing. Failure to complete a pulse train chain correctly is 'recognition failure' or 'irrelevant recognition' (1982, pp.183-185). The indexing of this probability of failure via the ERP is now discussed.

The Hendricksons conceptualised the ERP as "a waveform which is the pure response of the brain to the stimulus" (A.E. Hendrickson, 1982, p.189). As discussed in Chapter 1 this conceptualisation is not correct. Idiosyncratically, the Hendricksons further argued that the ERP waveform corresponds to the "summation of the individual pulses" (A.E. Hendrickson, 1982, p.191) by which they meant the summation of action potentials. Again, this is at odds with the description of ERPs given earlier. The Hendricksons' claim (e.g. A.E. Hendrickson, 1982, p.191) was based on a paper by Fox and O'Brien (1965) and similar studies with similar findings.

Fox and O'Brien's (1965) result is interesting. However, because it involved deep intracortical recording, a technique which for obvious practical and ethical reasons is not generally available for research with human subjects, it does not seem to have any direct relevance to the nature of EEG or ERPs recorded at the scalp. Also cited by A.E. Hendrickson (1982), Creutzfeldt, Rosina, Ito and Probst (1969) recorded both intracortically and epicortically (from the exposed surface of the visual cortex). Their results suggest far less correspondence between the temporal firing pattern of individual cortical cells and the epicortical ERP than is required by the Hendricksons' model. This reduced correspondence would be exacerbated when recording from scalp electrodes, by the volume conduction properties of the intervening tissues and the high resistivity of the skull.

The Hendricksons' theory and their interpretation of the ERP as "a kind of picture of the individual pulse trains" (A.E. Hendrickson, 1982, p.192) led them to propose that ERPs would show differences according to variation in intelligence. Their position was that the brains of less intelligent individuals exhibit errors in transmission of information. Moreover, the theory stated that errors in cortical transmission of information can be detected in the ERP.

Briefly, if no errors of transmission occur, the ERP averaging process would result in a faithful representation of the individual responses which would therefore be a complex waveform and have a longer string measure. On the other hand, the same averaging process carried out on a varying response would result in a more simple waveform. Therefore, high intelligence is equated with more complex waveforms.

2.2 The Hendricksons' data

The first ERP experiment that the Hendricksons reported appeared in the first paper under discussion (Hendrickson & Hendrickson, 1980) and was, presumably, based on D.E. Hendrickson's doctoral dissertation (see reference in the 1980 paper). In this experiment 93 students with an average age just under 21 years took part. For EEG recording the subjects were presented with auditory stimuli consisting of 400 ms, 1000 Hz tone pips at three levels of intensity (60 , 80 and 100 dB). All subjects were presented the stimuli in the same order, with randomly selected inter-stimulus intervals of 4, 6 and 8 seconds; subjects apparently responded to each stimulus, as in a simple reaction time procedure, although no details are given. The EEG was sampled and digitised at a rate of 2000 Hz from a bipolar asymmetrical montage Cz-T4. This type of montage may not have given the classical sequence of peaks seen with a monopolar montage. Electrode placement corresponded to that of the earlier ERP work of Ertl and Schaffer (1969), the results of which the Hendricksons utilised in the subsequent development of their string measure. Subjects also completed the Alice Heim 4 intelligence test (AH4), the WAIS digit span subtest and the Eysenck Personality Questionnaire. Their results were only summarised in the paper but essentially the outcome was that earlier peak latency was negatively correlated with IQ and higher peak amplitude was positively correlated with IQ. Correlational results for IQ with ERP latency and amplitude were consistent with previous research using similar recording montages.

As described in both the 1980 paper and in A.E. Hendrickson (1982), the next step in the development of their ERP measure of 'biological' intelligence was the application of the notion of degradation of the ERP. As described above, this degradation results from cortical transmission errors(that is, in recognition of pulse trains). The application of this idea involved measuring the "circumference of the waveform envelope ... if we thought of the waveform as a piece of string and went a standard length into the record, cut the string at that point, and pulled it straight, the high-IQ people would have longer waveform strings than the low IQ people." (A.E. Hendrickson, 1982, p.195). Unable to utilise their own data, they tried their method on some published waveforms of Ertl and Schaffer (1969). Before discussing the Hendricksons' findings, Ertl and Schaffer's paper will be reviewed. An issue pertaining to D.E. Hendrickson's (1982) discussion of technical issues relating to the string measure will also be raised.

Ertl and Schaffer (1969) were concerned to establish the existence, or otherwise, of correlations between ERP latency and IQ. Their sample consisted of 573 primary school children. Their age range was not given but they were in grades 2, 3, 4, 5, 7 and 8, and so it may be assumed that ages were between 7 and 13 years. The children completed three tests of intelligence, the Wechsler Intelligence Scale for Children (WISC), the Primary Metal Abilities test (PMA) and the Otis quick scoring mental ability test. They also underwent a visual evoked potential procedure consisting of "bright photic stimuli of microsecond duration ... delivered according to a uniform stimulus interval which ranged from .8 to 1.8 s" (Ertl & Schaffer, 1969, p.421). The stimuli were presented with the eyes open in a darkened room. EEG was recorded from a bipolar asymmetrical montage of two electrodes 6 cm apart astride C4 and parallel to the midline (refer to Figure 3.1, Chapter 3, to clarify this configuration). ERPs were constructed from 400 presentations of the stimulus and peak identifications were confirmed statistically via a zero-crossing analysis (Ertl, 1965). The latencies of each of the first four peaks so identified were used in the correlational analysis and a significant inverse relationship between each peak latency and IQ was found. However, it must be borne in mind that these latency measures are not necessarily comparing the same peaks across individuals because the montage is not monopolar but bipolar asymmetrical (according to the classification described in Chapter 1). Ertl and Schaffer recognised this and noted that "the ERPs of high IQ subjects are more complex, characterized by high frequency components in the first 100 ms" (1969, p.422). This observation will assume some importance when the discussion turns to the Fourier analysis of ERPs (see Chapter 4, below). Ertl and Schaffer (1969) published sample ERPs and WISC IQ scores from 20 subjects and it was upon these data that the Hendricksons tested their string measure. It should therefore be noted, in this regard, that D.E. Hendrickson (1982) later stated that, according to her theory, visual stimuli should be avoided because the use of such stimuli precludes the ideal that "the same population of receptor cells should fire with the same pulse train pattern with each presentation of the stimulus." (p.210). Nevertheless, their initial application of the string measure was based on Ertl and Schaffer's sample of visual ERPs.

The Hendricksons photocopied the published ERPs. In the 1980 report it was stated that the photocopy was enlarged but this was not mentioned in the 1982 report. This issue is important in light of a comment on the string measure by Veterelli and Furedy (1985) and the subsequent dismissal of this comment by Barrett and Eysenck (1992a, pp.262-263). This matter will be returned to shortly. After the photocopying, a piece of cotton was superimposed on the ERP trace, the cotton was cut and then straightened and measured. The correlation between the 'string length' and WISC IQ for these 20 individuals was .77. In the 1982 report it is acknowledged that this correlation may have been inflated because of the use of extremes of IQ by Ertl and Schaffer (1969) when publishing examples of ERPs. Robinson (1993; Haier, Robinson, Braden & Williams, 1983) also pointed this out.

Returning to the Veterelli and Furedy (1985) comment on this work, it seems that they were concerned with the matter of the enlargement, during photocopying, of the published ERPs and whether this distorted the result obtained; they maintained that the magnitude of the Pearson correlation coefficient found will change if the ordinate to abscissa ratio is increased. Veterelli and Furedy (1985) also noted that the string measure the Hendricksons used in their own work (D.E. Hendrickson, 1982) does not return a length at all and, therefore, they referred to it as a 'revised' string measure. Veterelli and Furedy (1985) applied the 'revised string measure' to Ertl and Schaffer's (1969) ERPs and found a correlation of .8; that is, the same as Hendrickson and Hendrickson (1980) found using a piece of cotton. However, they also applied it to some ERPs published by Weinberg (1969), in the same year and in the same journal as Ertl and Scaffer's ERPs. In this case the correlation with the published IQ scores was –.34. This aspect of Veterelli and Furedy's comment on the string measure was not mentioned in Barrett and Eysenck's (1992a) criticism of their paper but it appears to be of some importance in interpreting results obtained with the measure. (This is because Weinberg found a negative correlation between IQ and low-frequency event-related activity).

Given their success with the use of Ertl and Schaffer's (1969) data, the Hendricksons next undertook a study in association with Blinkhorn and subsequently a further study of their own (Blinkhorn & Hendrickson, 1982; D.E. Hendrickson, 1982). The Blinkhorn and Hendrickson (1982) results have been summarised in both Hendrickson and Hendrickson (1980) and D.E. Hendrickson (1982); the account in Blinkhorn and Hendrickson (1982) gave more detail but it is not entirely clear which form of the string measure was used. The interpretation here is based on a statement by D.E. Hendrickson that "data were obtained from this sample using the techniques described here, but our analysis procedures had not been completely established then. Our string measure ... was computed." (1982, p.197). As well, Blinkhorn and Hendrickson's (1982) reference to the Hendrickson and Hendrickson (1980) finding, based on the Ertl and Schaffer (1969) ERPs, is that the string measure was calculated using the piece of thread technique. Blinkhorn and Hendrickson (1982) used a sample of 36 undergraduates (age range, 18 to 36 years). The EEG was recorded from an electrode at Cz referred to a mastoid, that is a monopolar derivation according to the terminology used here, although Blinkhorn and Hendrickson (1982) referred to it (technically correctly) as bipolar. Subjects listened to 30 ms, 1000 Hz tone pips played through headphones at 85 dB. There was a random inter-stimulus interval which varied between 1 and 8 seconds. All subjects had completed Raven's Advanced Progressive Matrices (APM) and a subset of the sample had completed 'various other psychometric tests'. ERPs, of 512 ms duration (post-stimulus), were constructed from either 32, 64 or 90 epochs of EEG; string measures were obtained and correlations calculated. The mean correlation between the string measure and APM score was .45; no significant correlations were obtained with the other psychometric measures which were all verbal tests. The correlation with the APM is lower than the correlation Hendrickson and Hendrickson (1980; D.E. Hendrickson, 1982) found when utilising Ertl and Schaffer's ERPs. Blinkhorn and Hendrickson (1982) attributed this to restriction of range in the sample of APM scores and corrected their correlation, thus inflating it to a comparable size. However, Robinson (1993) noted that such attenuation of range should not be an issue if the population correlation is high, as the Hendricksons suggest.

D.E. Hendrickson's (1982) large scale study is now considered. In this study there was one main sample of 219 school age children (mean age 15.6, *SD* = 1.13 years) and three small samples; one was of 19 Mensa[2] members (mean age 28.7, *SD* = 6.54 years); another was of 16 law court clerks (mean age 42.4, *SD* = 9.57 years); the other was of 15 'severely sub-

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[2] Mensa is a club for people with high IQ (as tested by a purpose designed test) and a desire to belong to such a club.

normal' subjects whose results were only discussed in general terms. The EEG recording details were as follows. The stimuli were 30 ms, 1000 Hz tone pips delivered via headphones at 85 dB. The sine wave was always switched at a zero crossing point. Tones were presented with interstimulus intervals varying between 1 and 8 seconds; all subjects received the same set of intervals. The electrode montage was Cz referred to a mastoid. The EEG was unfiltered in the sense that the amplifier was purpose built and did not incorporate any analogue filters and therefore sampled in an unattenuated fashion up to 1000 Hz. This was thought to be important because "our interpretation of the EEG activity means that we should be able to detect the rise and fall of individual spikes if possible." (D.E. Hendrickson, 1982, p.210). This question of the high frequency content of ERPs will assume importance in later discussions.

As to the ERP/EEG measures reported, there are several issues to consider. The *string measure*, as noted by Veterelli and Furedy (1985), did not correspond to the previously used piece of cotton technique, even conceptually. Rather than presenting a formula for calculating the measure, six lines of FORTRAN code were given (D.E. Hendrickson, 1982, p.201). When these are translated, the measure turns out to be an averaged (over an epoch length) sum of squares of differences in amplitude (voltage) between consecutive points (time) of the ERP.[3] The *variance measure*, too, appeared as FORTRAN code and is the mean variance of the ERP calculated over a particular epoch. What this variance measure is concerned with, then, is the variability of the EEG on which the ERP signal is 'superimposed'. The *multiple string score* was also based on raw EEG and involved applying the string measure formula to the raw EEG. The *zigzag score* was a measure that indexed the number of times the raw EEG waveform changed direction over the epoch. The *composite*

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[3] Some characteristics of this formulation are discussed further in Chapters 3 and 4.

variance minus string score was computed by simple subtraction of raw scores. In other words, it takes a variance measure of the raw EEG and subtracts an averaged sum of squares of averaged raw EEG (averaged with the aim of cancelling out random ongoing EEG) and thereby loses sight of any physiological bases the measures might have. In consequence of this review of the measures employed by the Hendricksons, the only measure that will be dealt with here is the string measure because it is the only measure based solely on the event-related part of the EEG recording.

The school-age group and the court clerks were administered the WAIS and the Mensa group provided their 'official Mensa IQ score' (i.e., this was not a validated score). The results for the sub-groups of the sample will be discussed separately. The school-age group consisted of 140 children tested in a laboratory setting and drawn from an area of London described as 'working class' (18 of these children did not attend school); and 79 schoolchildren from an area described as 'middle to upper middle class'. The latter group was tested at their school with portable equipment. Robinson (1993) has pointed to a possible confounding factor in this arrangement, given the known correlation between socio-economic status and IQ on one hand and arousal and ambient noise on the other. Thus, the middle class group with higher IQs were tested under conditions which may have had higher ambient noise and, if so, these circumstances could have contributed to the findings reported. Correlations between the string measure and the subtests of the WAIS ranged from .32 for the digit symbol to .62 for vocabulary. The correlations with the IQ scales were .62, .53 and .72 for verbal IQ (VIQ), performance IQ (PIQ), and full scale IQ (FSIQ) scales, respectively. Of note is that the string measure correlated more highly with the verbal measures. The report commented that "our measures correlate rather more highly with the verbal subtests than the performance subtests. However, the same may be said of the full WAIS IQ measure itself." (D.E. Hendrickson, 1982, p.205). This pattern of results has been found subsequently (Stough, Nettelbeck & Cooper, 1990) and perhaps says more about the nature of the Wechsler scales than any relation of ERPs to 'biological' intelligence. This point will be returned to in the discussion on models for cognitive abilities in Chapter 5.

The Mensa sub-sample supplied their own IQ scores and these were 'scaled down' to equate them with WAIS scores. The mean IQ for this group was reported as 147.2 (*SD* = 5.7) and the correlation with the string measure was –.06. For the court clerk sample, correlations with the subtests of the WAIS ranged from –.24 for the digit symbol to .81 for block design. The correlations with the IQ scales were .54, .84 and .80 for VIQ, PIQ, and FSIQ, respectively. There was no suggestion here of the string measure being more related to the verbal measures; rather it was more highly correlated with the performance scales. A possible explanation for this may reflect that verbal abilities are an obvious job requirement for law court clerks and there was a markedly restricted range on the verbal scale; mean VIQ was 128 (*SD* = 10). The mean string measure for the Mensa group was longer than for the school age sample (249 vs 139; arbitrary units were reported) as well as longer than for the court clerk group (249 vs 197). Thus there was a monotonic relationship between the string measure and FSIQ across the three samples.

In summary, this review of the work of the Hendricksons has discounted the theoretical basis for the string measure on a range of objections at various levels of the model. It has been shown that the result obtained by applying the measure to the sample ERPs published by Ertl and Schaffer (1969) may have overestimated any correlation and, in any case, the methodology used by Ertl and Schaffer (visual modality, bipolar asymmetrical montage of electrodes) is expressly contraindicated by D.E. Hendrickson in her recommendations for obtaining string measure data. Blinkhorn and Hendrickson (1982) reported a mean correlation of .45 between a version of the string measure and APM which is taken at face value rather than correcting for attenuation of range. D.E. Hendrickson (1982) reported correlations ranging from –.06 to .84 between the string measure and the WAIS IQ scales, the mean correlation being .58 and the median correlation .68. These results were impressive enough to warrant further investigation of the relationship between the string measure and intelligence test scores. Before reviewing research inspired by the Hendricksons' work, some earlier but related work is described.

2.3 Earlier 'string-like' measures

This section describes work that pre-dated the Hendricksons but that also used some measure of the contour length of the ERP. Deary and Caryl (1993) have previously provided an account of this work. To some extent the discovery of earlier work utilising such measures validated the work of the Hendricksons, even though there was no theoretical link between the measures.

The use of an excursion measure arose from the work of Beck and Dustman and their colleagues beginning in the early 1960s (Dustman & Beck, 1963, 1965, 1966). These were studies of visual modality ERPs (VERP) and were concerned with the stability over time of the VERP and the effects of maturation and ageing on the VERP. Comparisons of the VERP in twins were also made. The excursion measure first appeared in Dustman and Beck (1965) and it was utilised as a way of comparing VERP waveforms within given epochs between groups; in this instance it was applied as a measure of differences between groups of different ages. A similar study appeared several years later (Dustman & Beck, 1969). In the same year the measure was used to compare the VERPs of groups of 'bright and dull' children (Rhodes, Dustman & Beck, 1969). In these studies a 'map-wheel' was used to trace out the waveform, and thus it literally did return a measure of excursion length.

In the Rhodes et al. (1969) study, comparisons of various ERP parameters (including waveform excursion of epochs 0-250 ms, 0-100 ms and 100-300 ms post-stimulus) were made between two groups of 20 children matched for age and sex but differing in IQ (measured with the WISC). One group ranged in FSIQ between 120-140 (mean 130) and the other group ranged between 70-90 (mean 79). EEG was recorded from four electrodes: C3, C4, O1 and O2, all referred to the ear lobes. The stimuli were reflected light flashes delivered at three intensity levels and ERPs were constructed separately from 100 presentations at each intensity level. For the purposes of this discussion the results to note are that the excursion measures of later deflections (100-250 ms), both occipitally and centrally, were longer for the bright children. However, examination of the published group average waveforms (p.366) reveals that this difference in excursion measures was attributable, *at the central electrodes*, to the P100-N140-P200 complex differing in amplitude; the brighter children having the greater amplitude response. At the occipital electrodes it is not clear what the difference resulted from. Other differences were found between the groups utilising the excursion measure but it must be emphasised that these differences were all reported in terms of describing various amplitude differences. The Rhodes et al. article will be returned to in this context, later. In summary, this paper found the same relationship between the excursion measure and IQ that the Hendricksons reported with their string measure—that is, a positive relationship. The finding is in the visual modality and extends to ERPs recorded occipitally. This is therefore a second successful example where procedures vary from recommendations by D.E. Hendrickson (1982) who argued that, according to her theory, the string measure should not be used with VERPs.

Finally, this group of researchers (Lewis, Dustman & Beck, 1972) also introduced another measure, the cumulative voltage change (CVC), that was very similar to the formulation of the string measure reported in D.E. Hendrickson (1982). The next section reviews research that has appeared since the Hendricksons' theory appeared. One issue that will be addressed is that of the different methods of indexing waveforms that have been used;

some of these are very similar to the CVC measure of Lewis et al., while others have been actual estimates of waveform excursion.

2.4 The string measure since the Hendricksons

The first reported independent test of the string measure appeared in Shagass, Roemer, Straumanis and Josiassen (1981). These workers were concerned with the possible influences of intelligence differences on ERPs and whether these influences should be considered in the clinical application of ERPs to patients with psychopathologies. Their subject pool consisted of 140 psychiatric patients and 90 nonpatient controls, all of these people completing Raven's Standard Progressive Matrices (PM). Their final sample was 100 participants; 40 pairs of patients matched for diagnosis, age and sex with one of each pair having a PM score above the median patient score and the other a score below that median, and a control group of 20 nonpatients selected so as to constitute a full range of PM scores. The mean PM scores for experimental and control groups were 53.6 (*SD* = 30.6) and 61.1 (*SD* = 27.3), respectively. EEG was recorded from 15 scalp electrodes (one of these served as an artefact channel) referred to linked ears; sampling rate was 1000 Hz. The EEG amplifier had a high frequency cutoff of 3000 Hz (well above the 1000 Hz recommended by D.E. Hendrickson, 1982). Stimuli were presented in three modalities; somatosensory stimuli were electrical pulses delivered to the wrists (separately) at 10 mA above threshold; auditory stimuli were binaural clicks delivered via headphones at a level 50 dB above 75 dB white noise; visual stimuli were 8 msec presentations on a video monitor of a checkerboard pattern with a mean intensity of 1.2 ft-L and viewing distance 4 ft (1.2 m). These stimuli were presented in pseudo-random order with no two consecutive presentations of the same stimulus. ERPs were constructed from 192 epochs of EEG for each modality. For the purposes of their experiment various amplitude and latency measures were computed and the high and low IQ groups were compared.

Additionally, Shagass et al. (1981) also considered 56 possible correlations between string measure and PM score (i.e., 4 ERP measures by 14 scalp electrodes). For the control group of 20 subjects none was significant. For the patient group of 80, seven were statistically significant ranging from –.22 to –.31. That is, these seven correlations were all in the *opposite* direction than predicted by the Hendricksons' theory.

Eysenck and Barrett (1985, p.25) criticised this finding on several grounds. The first criticism concerned the use of multi-modal stimuli rather than tone pips of specified frequency and sound level and to the method for calculating the string measure (Shagass et al. calculated a waveform excursion measure). This criticism is weakened by the fact that Hendrickson and Hendrickson (1980) had used visual ERPs in their first demonstration of the measure. Secondly, Shagass et al. were criticised for transforming PM scores to take account of age differences. However, this was done according to instructions in the test manual and seems to be no different than the procedure involved in calculating WAIS IQ, for instance, where scores are normalised according to age. Another issue raised was whether some of the results reported in this paper were calculated on only a small sub-sample of 14 controls. These were age matched control pairs used for comparison with the results from the 40 matched patient pairs and therefore did not bear on the string measure correlations. A later review (Barrett & Eysenck, 1992a) pointed only to the use of visual stimuli as a reason for the failure to replicate the Hendricksons' findings. A second paper (Barrett & Eysenck, 1992b) was even less critical in light of their own failed replication attempt (see below).

Deary and Caryl (1993) also discounted the possible significance of Shagass et al.'s (1981) results but understandably so because they were concerned with comprehensively summarising a very complex body of literature. With the benefit of being able to appraise the more recent developments in the field, the current author believes the Shagass et al. paper fits a pattern; this pattern has led to the development of a new theory on the string measure which is presented in Chapter 4 of this thesis.

Haier, Braden, Robinson and Williams (1983) were concerned with the extent to which the intensity of the stimuli used in an ERP paradigm affected any relationship between ERPs and IQ. Their sample was 23 nursing students (mean age 22.1, *SD* = 4.34 years). Stimuli were 500 ms duration light flashes at four intensities (4, 18, 75 and 320 ft-c) presented via a translucent screen in a darkened room. The order of presentation of intensities was pseudo-random, at a rate of 1 presentation per second, with 64 presentations at each intensity. EEG was recorded from Cz referred to the right ear at a sampling rate of 250 Hz; the EEG was bandpass filtered from 0.4 to 40 Hz. Subjects took part in two consecutive sessions and ERPs were constructed for each session. The string measure calculated was an excursion measure and the average of the two sessions was used. String measures were calculated at three epoch lengths (0-508, 0-252 and 252-508 ms) for each of the four stimulus intensities. Correlations with APM scores ranged from .13 to .50; the higher (and significant) correlations being associated with the higher intensity stimuli at *all* lengths of string. Haier et al. (1983) also demonstrated that these string measure correlations with APM were almost entirely determined by the amplitude of the N140-P200 complex.

Sandman and Barron (1986) studied 39 institutionalised, severely retarded adults. The sample consisted of 22 subjects who worked in a structured workshop; these were matched with 17 others who were not in a structured workshop. Subjects completed the Peabody Picture Vocabulary Test (PPVT). Results indicated that the two groups differed significantly on IQ, the former group having a mean IQ of 32.8 (*SD* = 15.9) and the latter group 16.6 (*SD* = 5.7). EEG was recorded from C3 and C4 referred to linked mastoids at a sampling rate of 1000 Hz. Stimuli were 600 Hz tones. Two separate complexity measures were calculated by summing the absolute values of successive peaks and then dividing by the latency of the last peak included in the measure. One measure terminated at the P2 deflection and the other at the N2 deflection[4]. Correlations between these complexity measures and IQ were calculated for the whole sample and for the two groups separately. Not one was significant.

Mackintosh (1986), in the course of a discussion and review on the question of the heritability of intelligence, reported the results of a study he conducted at Cambridge University with several of his colleagues. Few details are given but apparently the Hendricksons' procedures were employed; the sample was 18 subjects and correlations of –.33 and –.34 were obtained with the APM and the Mill Hill Vocabulary scale, respectively. Again, the direction of correlations was opposite to that found and predicted by the Hendricksons (Blinkhorn & Hendrickson, 1982; Hendrickson & Hendrickson, 1980; D.E. Hendrickson, 1982).

Vogel, Kruger, Schalt, Schnobel and Hassling (1987) did not report data concerning the string measure directly. They used an independently developed measure which they stated was comparable to the Hendrickson string measure, in that it was a combined measure of amplitudes. This measure was termed the 'oscillation' measure of the ERP and was a sum of peak-to-peak amplitudes, calculated using the first six peaks (defined as subsequent local extreme values) of an ERP. Vogel et al. (p.175) argued their measure was superior to the Hendrickson string measure in that it avoided three disadvantages of the string measure: "Firstly, its dependence on sampling rate (the string measure generally increases with decreasing sampling frequency)[5]; secondly, an incomplete assessment of local extreme values

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[4] The nomenclature for the deflections is that of these authors. This system labels deflections according to their sequence and polarity. The other system commonly used labels deflections according to polarity and latency (although the latency may be generic in the sense that, for example, P300 has been reported with latencies from about 300 ms to 500 ms, or longer).

[5] The author has confirmed this characteristic of the string measure (as calculated by D.E. Hendrickson's formula) by recording gated sine waves of various frequencies at various sampling rates. For any given frequency sine wave, the magnitude of the string measure is a decay function of increasing sampling rate.

of the amplitude, if they occur between two samples; and finally, the disproportionate influence of strong alterations of amplitude per unit time". In addition to calculating correlations based on their own measure, Vogel et al. calculated and tested the Hendrickson string measure but did not report the results because they were only trivially different from the results obtained using the 'oscillation' measure. Subjects were 236 university students selected from a larger pool on the basis of characteristics of their EEG. Subjects completed tests of intellectual performance and personality. Those of interest here are the Intelligenz-Struktur-Test (IST), which yielded an IQ score, and the PM. Both visual and auditory ERPs were recorded, the former to light flashes at four intensities (590 L, 1700 L, 4900 L and 10,000 L) and the latter to 500 ms duration 500 Hz tones. All stimuli were presented in pseudo-random order with both constant and variable interstimulus intervals; separate ERPs were constructed for both sets of stimuli. EEG was recorded from F4, Cz, P4, O1 and O2, all referred to the right ear and sampled at a rate of 333 Hz. EEG was filtered, such that at 70 Hz amplitude was diminished by approximately 70%. Vogel et al. reported results only from Cz and for stimulus presentations with randomised time intervals but noted that for other electrodes and for the constant interstimulus interval condition the results did not differ. Thus they reported five correlations (four visual ERP and one auditory ERP) with each of the two intelligence test scores. No correlation exceeded .1 in magnitude and all were nonsignificant. Given the large sample size and the technical excellence of this experiment, this is a very important result.

Stough et al. (1990) sought to remedy a perceived lack of adherence to the Hendricksons' recommendations when obtaining string measure correlations with IQ. They also sought to explore the nature of correlations with verbal as opposed to performance IQ

For practical purposes—that is, with sampling rates typically used in ERP research and with constant sampling rate across conditions or subjects, this characteristic of the string measure will not affect correlations with IQ.

scales. Their subjects were 20 first-year psychology students (mean age 18.9, *SD* = 0.83 years). EEG was recorded from Cz referred to the left mastoid and stimuli were the same as employed by Blinkhorn and Hendrickson (1982) and D.E. Hendrickson (1982), with the exception that the intensity of the tone was 70 dB rather than 85 dB. The EEG was bandpass filtered between 2 and 125 Hz. The formula employed for calculating the string measure was functionally identical to that presented by D.E. Hendrickson. Stough et al. reported correlations between the three WAIS-R scales as well as raw APM scores and various epoch length string measures (0-100 ms, 100-200 ms, 0-250 ms, 0-200 ms and 100-300 ms); they reported uncorrected correlations and correlations corrected for restrictions in range and test reliability. The uncorrected correlations ranged from –.26 to .71, with mean and median .31 and .37, respectively. These correlations, calculated over various overlapping epochs, will not be independent.

The highest correlations reported by Stough et al. (1990) were between string 100-200 ms and VIQ, and FSIQ; correlations with APM scores were near zero or negative. This pattern of correlations in part reproduces the finding of D.E. Hendrickson (1982) of a higher correlation with VIQ than with PIQ (see discussion above). However, the correlation with APM is more akin to the findings of Shagass et al. (1981) and Mackintosh (1986) than those of Blinkhorn and Hendrickson (1982) or Haier et al. (1983). Stough et al. (1990) pointed to a restriction of range in the APM scores to account for their results. Blinkhorn and Hendrickson (1982) suggested the same factor accounted for their correlations being in the mid .4s (rather than being about .8 as found by D.E. Hendrickson, 1982). Blinkhorn and Hendrickson's sample had a mean APM score of 26.03 (*SD* = 4.33); Haier et al.'s (1983) sample had a mean APM score of 21.4 (*SD* = 5.54) and Stough et al.'s sample had a mean APM score of 26.5 (*SD* = 4.3). Shagass et al.'s (1981) and Vogel et al.'s (1987) samples completed the PM and so a direct comparison is not possible. However, given these APM ranges, it seems unlikely that the restriction in range fully explains Stough et al.'s finding.[6] An alternative conclusion is that the correlation of the string measure with IQ is not reliable. However, discussion of this possibility is deferred until this review has been completed.

Finally, Stough et al. (1990) addressed the finding by Haier et al. (1983), that the string measure correlations are determined by the amplitude of the N140-P200 complex. Stough et al. found no relationship between the amplitude of this complex and any of their intelligence test scores. It is difficult to reconcile this finding with other aspects of their results. This is because the N140-P200 complex lies within the epochs for which they found the highest correlations, so that amplitude would be expected to contribute to the string measure. Stough et al. offered no comment on this apparent contradiction and, because ERPs were not published in their report, it is not possible to clarify this outcome.

Gilbert, Johnson, Gilbert and McCulloch (1991) reported a small scale replication of D.E. Hendrickson's (1982) finding. Their sample was 21 schoolboys (age 13 or 14 years). EEG recording and stimulus presentation details were very similar to those utilised by D.E. Hendrickson, including no high frequency filtering of the EEG signal. Stimulus intensity was 80 dB and inter-stimulus intervals were between 1-7 sec. Subjects completed the SFT, Academic Aptitude. Gilbert et al. (p.1184) described their string measure as being "calculated for each subject in the manner described by Hendrickson (1982)". The correlation between the string measure and the test score was .41—i.e., the same magnitude and direction correlation as reported by Blinkhorn and Hendrickson (1982), Haier et al. (1983) and Stough et al. (1990).

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[6] Stough (1994) reported results for a total sample of 70 subjects, of which those reported in Stough et al. (1990) were the first 20 tested. In the larger sample, the median correlation of the string measure with APM was .31 ($p < .05$). This result was therefore consistent with those of Blinkhorn & Hendrickson (1982) and Haier et al. (1983).

Barrett and Eysenck (1992b) attempted a detailed replication of the Hendrickson procedure. This paper will now be comprehensively reviewed because it raises some important points in regard to the string measure. The subjects were 40 volunteers (age range 19 to 39 years) recruited from either the institution where the experiment took place or the local unemployment bureau. All subjects completed the WAIS-R and various personality questionnaires. Stimulus presentation was as described by D.E. Hendrickson (1982), with the exceptions that interstimulus intervals were randomised between 3-8 sec and each subject received a unique sequence of intervals. EEG recording was via five channels as follows: Cz referred to the left mastoid; Cz referred to the right mastoid; C4 referred to Oz; C3 referred to Oz; and O1 referred to O2. Two channels of electrooculogram (EOG) and one channel of electromyogram (EMG) were recorded to monitor eye movement and muscle artefact, respectively.

Barrett and Eysenck (1992b) calculated the string measure, as prescribed by D.E. Hendrickson (1982). They also calculated a mean absolute amplitude measure and an amplitude regression intercept.[7] All these measures were calculated over two epochs, 256 ms and 512 ms post-stimulus. Latencies of two deflections, N100 and P180, were also measured. Three separate analyses of the data were undertaken but only the first two are relevant to this review. The point of these two analyses was to test the effect of filtering the EEG prior to processing and averaging. This test arose because the Hendricksons argued that the high frequency components of the ERP should be included so as to ensure that the ERP was of adequate fidelity in regard to its reproduction of individual action potentials. In the first

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[7] This measure was calculated from a regression of *individual* evoked potential mean absolute amplitudes over epochs. Barrett and Eysenck (1994) reported that this measure (over a series of experiments) was inversely related to IQ but shared about 60% variance with the Hendrickson variability measure. Again, then this measure appears to capture some aspect of the EEG which is not event-related (see the discussion on D.E. Hendrickson, 1982, above).

analysis the EEG was as recorded, with a bandpass 0.8-300 Hz. In the second analysis the data were subjected to a 40 Hz digital low pass filter with characteristics such that activity in the 30-40 Hz region was severely attenuated (technical details of the filter are given in the paper). Barrett and Eysenck concluded their description of the filter with the statement that "this filter had the effect of removing *all* high frequency 'jitter' in an epoch" (p.368)[8]. The possibility that at least some of this high frequency activity is cortically generated and perhaps related to information processing is discussed in Chapter 4 (below).

In discussing the results reported by Barrett and Eysenck (1992b) some condensation will be necessary. Firstly, the results for the 256 ms and 512 ms epochs were virtually identical and the 512 ms epoch results are therefore not considered here. Secondly, the results for Cz-left mastoid and Cz-right mastoid were very similar, therefore only Cz-left mastoid is considered. (This channel produced slightly higher correlations and Barrett and Eysenck reported only this channel when presenting results of the second analysis—i.e., digitally filtered data). Thirdly, because channels C3-Oz and C4-Oz gave near identical results, thereby indicating that there was no lateralisation of ERP response, only C4-Oz will be discussed. For the first analysis (i.e., not digitally filtered) correlations between the string measure and VIQ, PIQ and FSIQ were –.37, –.49, –.44 (Cz-left mastoid) and –.17, –.28 and –.23 (C4-Oz), respectively. The correlations were in the opposite direction t that predicted by the Hendricksons' theory. Similarly, for the second analysis (where the EEG was digitally filtered) correlations between the string measure and VIQ, PIQ and FSIQ were –.16, –.22, –.19 for Cz-left mastoid (the results were not reported for the other channels, but it was noted that the filtering affected only the string measure). This finding of a reduction in magnitude

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[8] Dr. Barrett (personal communication, February 10, 1996) has used this term from electronic engineering to refer to high frequency muscle potentials and other high frequency noise and harmonics recorded along with the cortical potentials.

of correlations when the EEG data are filtered is important because the string measure seems to be dependent on the frequency composition of the ERP.

Widaman, Carlson, Saetermoe and Galbraith (1993) investigated the relationship between parameters of auditory ERPs and two factors, which they argued represented fluid and crystallised intelligence (designated Gf and Gc, respectively)[9]. These factors were extracted from scores on seven subtests of the WAIS-R (namely, Information, Vocabulary, Comprehension, Similarities, Picture Completion, Picture Arrangement and Block Design) and from scores on Raven's PM (Forms A, Ab and B). Subjects were 48 undergraduate psychology students (mean age 19.7 years, *SD* = 2.6). EEG was recorded at a sampling rate of 1000 Hz from Cz, T3 and T4 referred to linked mastoids. The EEG was bandpass filtered from 1-100 Hz.. Stimuli were binaural clicks of 0.1 ms duration at three intensity levels (65, 75 and 85 dB) and presented with an interstimulus interval of 2 s. Stimuli at each intensity were presented 64 times and there were four repetitions at each level. Order of intensities was randomised. ERPs were constructed from the average of all presentations at each intensity level. Deflection latency and peak-to-peak amplitude measures were calculated, as well as a string measure based on the ERP excursion. The ERP measures were tested for correlation with Gf and Gc factor scores, as well as on a *g* factor obtained by summing these scores. There were 27 correlations calculated for the string measure (3 electrodes, 3 stimulus intensities, 3 factor scores). Of these, only two were statistically significant and in the opposite direction to that predicted by the Hendricksons.

Bates and Eysenck (1993) recorded EEG whilst subjects were engaged in an inspection time (IT) estimation. There were 70 subjects (mean age 32.3, *SD* = 12.02 years). All subjects completed the Multiple Abilities Battery (MAB), the IT estimation (concurrent

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[9] Horn and Cattell's theory (from which these constructs derive, see e.g., Horn, 1985), commonly designated Gf–Gc theory, is discussed in Chapter 5 of this thesis.

with EEG recording), various reaction time (RT) tasks and the Eysenck Personality Questionnaire (EPQ-R). EEG was recorded from 19 scalp electrodes referred to linked ears, two of these electrodes serving to detect eye-movement artefact. EEG was bandpass filtered from 0.8-300 Hz and was sampled at a rate of 1024 Hz. The stimuli were of two types: the first was a dual modality preparation cue presented prior to the onset of the IT stimulus and the second was the IT stimulus itself. The preparation cue consisted of a 50 ms, 1000 Hz, 70 dB tone played through headphones and presented synchronously with the lighting of a fixation point on the LED display that presented the IT stimuli This fixation point was lit for the whole of a variable (1-3 s) 'preparatory period'. The IT stimulus itself was lit for a variable period (according to the subject's performance) and was then replaced by a mask consisting of additional LED units. ERPs were constructed to the onset of the preparation cue and to the onset of the IT stimulus and were of 650 msec duration (500 ms post-stimulus). The number of epochs of EEG used varied between 75-100. The EEG was digitally bandpass filtered from 0.5-40 Hz. Further, the table of correlations (Table 4, p.367) states that ERP data were low pass filtered 1-35 Hz.

Of 34 correlations (17 scalp electrodes, 2 stimuli) between string measure and MAB score, 13 were significant. The highest correlation was –.61; the mean correlation over electrodes and conditions was –.25 and the median correlation was –.27. These correlations between IQ and string measure were therefore in the opposite direction to that predicted by the Hendricksons' theory. Of 34 correlations between string measure and IT, 18 were statistically significant. The highest correlation was .77; the mean correlation over electrodes and conditions was .28, the median correlation was .30.

Barrett and Eysenck (1994) reported data from two studies supplemented with data drawn from Barrett and Eysenck (1992b), described above but on this occasion found no relationship between the string measure and IQ. Some details as to the two new studies reported in this paper are now given.

In Study 1, 74 subjects (age range 17 to 56 years), completed the WAIS-R and the APM (with a 20 m time limit) as well as personality questionnaires. EEG was recorded on two separate occasions and stimuli were as described in Barrett and Eysenck (1992b). EEG was recorded from Cz referred to linked mastoids and was bandpass filtered from 0.8-30 Hz. In Study 2, 86 subjects (age range 18 to 53 years) completed the MAB as well as personality questionnaires. EEG was recorded from seven scalp electrodes referred to linked ears and was bandpass filtered from 0.1-200 Hz. It was then digitally bandpass filtered from 0-30 Hz. Subjects undertook RT and IT tasks, including an IT estimation during EEG recording, but the ERPs were constructed from epochs of EEG recorded in response to the presentation of tones as in Study 1. There were two separate ERPs constructed to separate presentations of the series of tones. The string measure was calculated according to the formula of D.E. Hendrickson (1982). Barrett and Eysenck (1994) stated that "correlational analyses for studies 1 and 2 indicated no conceptually or statistically significant relationships between the ERP variables and psychometric IQ, on either of the test occasions or, in the case of study 2, across all 7 measurement channels ... it now seemed that we could not even replicate our prior results" (p.14).

In their introduction, Barrett and Eysenck (1994) suggested that heterogeneity of samples with respect to some unknown factor is responsible for the non-replicability of results in the research on individual differences in IQ. With respect to ERP research they stated that "the correlation between IQ and different aspects of the averaged evoked potential have often given dissimilar results. This may suggest the absence of any true relation, but there is too much meaningful agreement to make this hypothesis acceptable ... for some people there might exist a strong correlation between IQ and certain aspects of the ERP, while for others such a correlation might be lacking. [Our purpose is] the discovery of an objective indicator independent of IQ which repeatedly succeeds in splitting the total sample into a high- and low- correlation group" (p.4). Other workers have suggested alternative theories to account for the pattern of relationships found in the literature. That pattern is summarised in the next section. Bates' (Bates & Eysenck, 1993; Bates, Stough, Mangan & Pellett, 1995) theory is discussed and tested in Chapter 3.

2.5 Summary and discussion of the string measure research on IQ

Table 2.1 presents a summary of the studies reviewed. It will be seen that there appears to be no consistent pattern in these results. That is, there is no clear distinction between these studies in terms of whether primarily sensory ERPs (Barrett & Eysenck, 1992b, 1994; Blinkhorn & Hendrickson, 1982; D.E. Hendrickson, 1982; Gilbert et al., 1991; Haier et al., 1983; Sandman & Barron, 1986; Shagass et al., 1981; Stough et al., 1990; Widaman et al., 1993) or task-relevant ERPs (Bates & Eysenck, 1993) were used for the string measure calculations. Indeed, studies with near identical methodologies (Barrett & Eysenck, 1992b; D.E. Hendrickson, 1982) have produced different results and *vice versa.* Of the 14 studies considered,[10] 10 were of adequate power (i.e., .8; Cohen, 1988) to detect an effect of the size postulated by the Hendricksons. There appears to be no consistent relationship between

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[10] Only studies that have reported correlations of the string measure with IQ are considered. There are other studies concerned with the string measure (Bates et al., 1995; Robinson, 1997; Robinson & Behbehani, in press) and studies that have used the string measure in research on information processing (Stough et al., 1995) and these will be considered in later chapters. The contributions of Fidelman (1996a, 1996b) will not be considered because they are non-empirical and essentially speculative.

outcomes and the type of string measure calculated or the particular method used to calculate the measure. This is consistent with a finding reported by Nettelbeck and Batt (1994).

Table 2.1

Summary of studies that have calculated correlations between string measure (or variants) and IQ

Study	N	Power[a]	ERP Paradigm	ERP Measure[b]	Outcome[c]
Rhodes et al. (1969)	40	.92	Light flashes; WISC	Excursion–map wheel	+ve
Shagass et al. (1981)	100	> .995	Electrical pulses, Pattern reversal, Binaural clicks; PM	Excursion–triangulation	-ve
D.E. Hendrickson (1982)	254	> .995	Tone pips; WAIS	Complexity–formula	Mn = .58 Md = .68
Blinkhorn & Hendrickson (1982)	36	.89	Tone pips; APM	Excursion–cotton thread (?)	Mn = .45
Haier et al. (1983)	23	.71	Light flashes; APM	Excursion–formula	+ve
Sandman & Barron (1985)	39	.91	Tone pips; PPVT	Complexity–formula	zero
Mackintosh (1986)	18	.59	Tone pips (?); APM, Mill Hill Vocabulary scale	Complexity–formula (?)	-ve
Vogel et al. (1987)	236	> .995	Light flashes, Tone pips; IST, PM	Complexity–formula	zero
Stough et al. (1990)	20	.64	Tone pips; WAIS-R, APM	Complexity–formula	Mn = .31 Md = .37
Gilbert et al. (1990)	21	.66	Tone pips; SFT	Complexity–formula	.41
Barrett & Eysenck (1992b)	40	.92	Tone pips; WAIS-R	Complexity–formula	-ve
Widaman et al. (1993)	48	.96	Binaural clicks; WAIS-R, PM (Gf, Gc and G)	Excursion–formula	zero

Study	N	Power[a]	ERP Paradigm	ERP Measure[b]	Outcome[c]
Bates & Eysenck (1993)	70	> .995	IT stimuli; MAB	Excursion–formula	Mn = -.25 Md = -.27
Barrett & Eysenck (1994)	160	> .995	Tone pips; WAIS-R, APM, MAB	Complexity–formula	zero

[a] The power of each study has been calculated assuming a true effect size (i.e., correlation between the string measure and IQ) of .5. This was chosen because it falls halfway between the typical correlation between physiological and behavioural measures of .3 (Hunt, 1980) and the correlation of about .7 reported by D.E. Hendrickson (1982) and Stough et al. (1990). It is also the correlation found between IT and IQ in normal samples (Kranzler & Jensen, 1989; Nettelbeck, 1987). The question asked, then, was: if the true effect size is .5, what is the probability that the conclusion will be drawn that the effect size is greater than 0 ($\alpha = .05$, one-tailed) for a given sample size?

[b] The term "excursion" has used where some method of measuring or calculating the length of the ERP trace has been used. The term "complexity" has been used when some formula based on D.E. Hendrickson's (1982) complexity measure has been used or some measure intended to capture complexity rather than length has been used (e.g., Sandman & Barron, 1985; Vogel et al., 1987).

[c] The outcome refers to the correlation between the ERP measure and IQ and has been described as +ve, -ve, or zero. However, where possible both mean and median correlation coefficients have been given. In some cases (e.g., Barrett & Eysenck, 1994) so many correlations are reported that summarising them in this way was not feasible.

Chapter Three: The string measure, IQ and IT[11]

3.1 Introduction

As discussed in Chapter 2, Bates and Eysenck (1993) reported a *negative* correlation between the string measure of the ERP and IQ—that is, in the direction opposite to that predicted by the Hendricksons' theory. On the basis of this report a new theory of the string measure was proposed by Bates (Bates & Eysenck, 1993; Bates et al., 1995). This theory proposed that the relationship between the string measure and IQ depends on the attentional demands imposed by the experimental procedure. Specifically, if a procedure demands focussed attention then the string measure is held to index the *efficiency* of the brain. A more efficient brain will expend less metabolic energy in response to an attended stimulus than a less efficient brain and, according to Bates' theory, "will generate less time-locked string activity" (Bates & Eysenck, 1993, p.369). This means that the correlation between the string measure and IQ is negative. Conversely, where the procedure makes no demand for focussed attention, the string measure is held to index the *capacity* of the brain. The brain with greater capacity will expend more metabolic energy processing an unattended stimulus than will a brain with lesser capacity (Bates & Eysenck, 1993, p.370). This means that greater brain capacity equates with ERP complexity and the correlation between the string measure and IQ is therefore positive.

In support of their theory, Bates and Eysenck (1993) argued that the procedure used by Barrett and Eysenck (1992b) imposed attentional demands, although that study was a very close replication of the original D.E. Hendrickson (1982) study. Barrett and Eysenck (1994, pp.16-17) disputed this interpretation but Bates et al. (1995) maintained their initial position.

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[11] The material in this chapter has appeared, in somewhat different form, as Burns, N.R., Nettelbeck, T. & Cooper, C.J. (1996). The string measure of the event-related potential, IQ and inspection time. *Personality and Individual Differences, 21,* 563-572.

To elaborate, the argument was that the negative correlations between string measure and IQ reported by Barrett and Eysenck (1992b) arose because participants in that experiment were instructed to listen to tones presented via earphones. This was contrasted by Bates et al. (1995,) to the method "meticulously described by A.E. (sic)[12] Hendrickson (1982), [that] required subjects to listen to but not respond to the 100 auditory tones, so that no discrimination was required or implied" (p.31). No such description of the methodology is given by the Hendricksons. D.E. Hendrickson (1982) merely stated that tones were presented binaurally via headphones. For this and other reasons given in the note below the Bates' claim and theory are not convincing. The test of their theory that Bates et al. (1995) reported is now described.

Bates et al. (1995) stated that the most direct test of their attentional theory requires a demonstration that attention modulates the string measure in interaction with IQ. The experiment they described provided two conditions. The attended condition required that subjects listen to tones, 10% of which were a higher frequency than the rest, and count the higher frequency tones. For the other condition (unattended) subjects were instructed to ignore the tones. ERPs were constructed for both conditions (but not to the higher frequency tones in the attended condition). Twenty-one participants completed the AH-5 and the EEG recording. An analysis of covariance showed no main effect for either attention or IQ. However, the interaction term was "highly significant at several sites" (p.34). Given that

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[12] The introduction to this paper contains several errors, either of commission or omission. The reference to a description of subject instructions by A.E. Hendrickson (1982) should be to D.E. Hendrickson (1982) wherein the Hendricksons presented their experimental methodology and results. However, as noted here, the description there is not as claimed by Bates et al. These authors also erred in their description of the formula for the string measure provided by D.E. Hendrickson. Their review of the relevant literature was incomplete. For example, they reported a finding by Caryl and Fraser (1985) of a correlation of .8 in a sample of 10 undergraduates but did not mention the Vogel et al. (1987) study which had a sample of over 200 and reported correlations of the string measure with IQ that were near-zero. Caryl and Fraser did not publish their findings because they could not replicate them (Caryl, personal communication, 16th March, 1995). Bates et al. also did not include several other relevant studies in their review.

there were 20 electrode sites, more detail would have been helpful in interpreting this result. There is an issue here that can be resolved empirically.

As described in Chapter 2, Bates & Eysenck (1993) reported an experimental procedure wherein ERPs were recorded to the warning cues and target stimuli during an IT estimation procedure. Obviously, the IT procedure is a paradigm "which requires significant focused attention" (Bates et al., 1995, p.31). The test of Bates' theory in this chapter, to follow, used a similar protocol to that of Bates and Eysenck (1993) and to Caryl (1994) and Zhang et al. (1989a, 1989b). ERPs were recorded as subjects were presented with warning cues and target stimuli of the IT paradigm but, unlike the Bates and Eysenck (1993) study, each subject received target stimuli at only two SOAs. One SOA was set shorter than the previously determined estimate of the IT of the subject and the other was set longer than that estimate. These are referred to hereafter as the IT– and IT+ conditions, respectively.

With respect to the string measure of these ERPs, the Hendricksons' theory predicts a positive correlation between the string measure and IQ. However, Bates' theory predicts a negative correlation because of the attentional demands embedded in the IT procedure. As noted above, Bates and Eysenck (1993) also found substantial *positive* correlations between the string measure and IT. Of course, this is inevitable, given their finding, from which their theory derived, of negative correlation between the string measure and IQ given the negative correlation reported between IT and IQ (Kranzler & Jensen, 1989; Nettelbeck, 1987). On the other hand, the Hendricksons' theory would predict a negative correlation between the string measure and IT.

3.2 A direct test of Bates' theory[13]

3.2.1 Method

Subjects.

N = 40; 23 males and 17 females. Mean age was 24.2 (*SD* = 5.6) years. Twenty-four of the subjects were University students, with 16 drawn from the wider community.

Apparatus and materials.

EEG was recorded in a lead-plated cubicle lit at an intensity of 8 lx, measured at the subject, seated in a padded, high-backed armchair. Communication between the experimenter and the subject was via loudspeaker. EEG was recorded from 9 mm diameter dome-type gold-plated silver electrodes attached with Grass EC2 electrode cream at the midline frontal (Fz), vertex (Cz) and parietal (Pz) sites on the scalp according to the International 10/20 System (see Figure 3.1). These electrodes were referred to the left mastoid process. The electrooculogram (EOG) was recorded via cross-referenced electrodes attached in the horizontal plane at the outer canthus and in the vertical plane in the pupillary line just above the eyebrow of the left eye. A ground electrode was attached to the right mastoid process. Impedance was below 5 kΩ for the EEG electrodes and below 8 kΩ for the EOG electrodes. EEG and EOG signals were amplified by a Neomedix NEOTRACE 800ZF physiological recorder. Amplifier gain was set at 10,000 with the high frequency analogue filter set at 100 Hz and the low frequency analogue filter set at 0.5 Hz; a 50 Hz analogue notch filter was employed in each amplifier channel. Amplifier output was fed into a SCAN model 1098 12-bit DAS-100 kHz analogue-to-digital converter and from there to an IBM-compatible PC

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[13] Some of these data were collected as part of the author's Honours project. Specifically, EEG, IT and Digit Symbol from 31 subjects were collected as part of that project. For the Ph.D work, most of these subjects returned to complete the full WAIS-R. Additional subjects were recruited and they completed the full experimental protocol. None of the analyses reported here formed any part of the author's Honours project.

running SCAN EEG software which collected EEG data from single sweeps for off-line processing.

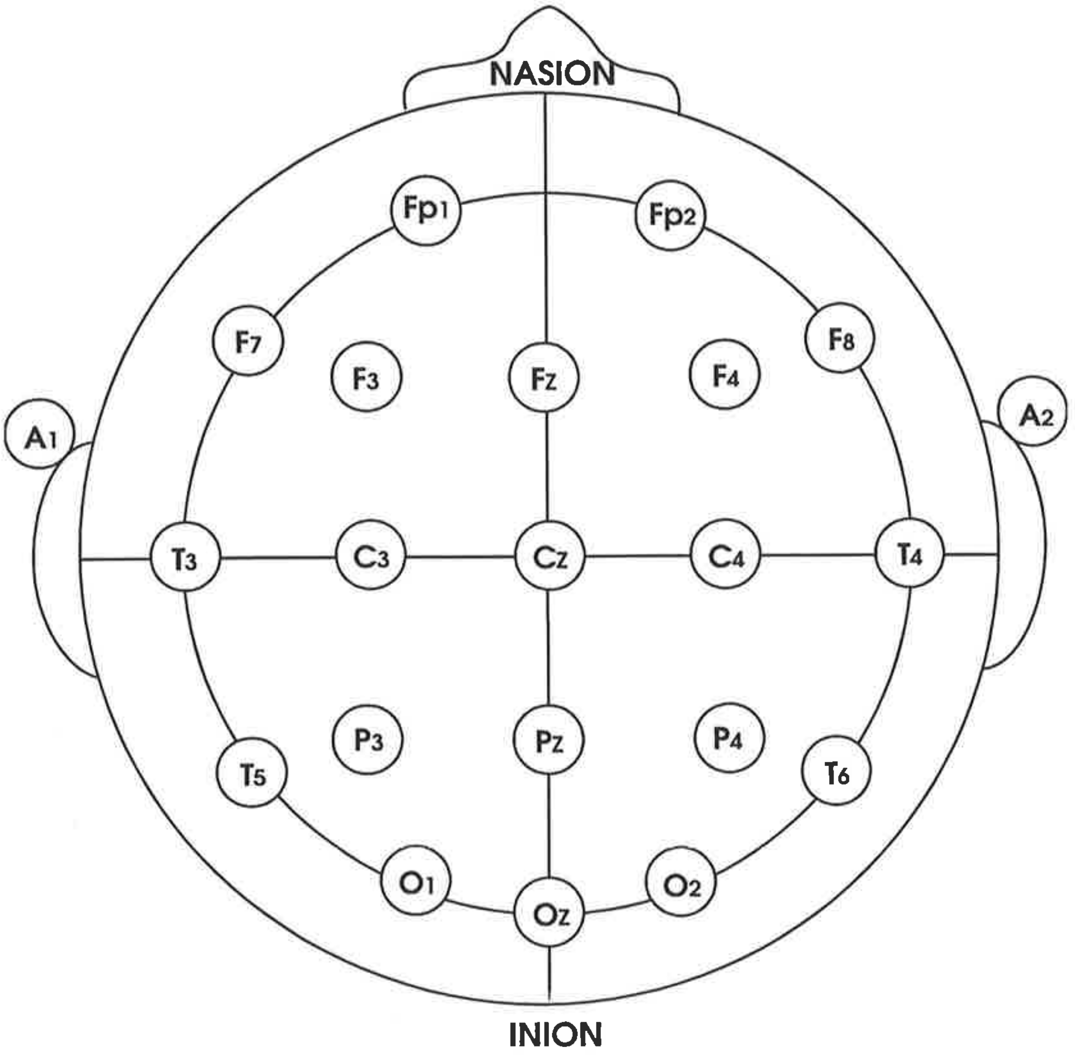

Figure 3.1. A single plane projection of the head showing the standard placements from the ten-twenty method of measurement. Measurements (ten per cent and twenty per cent) are based on the distances from nasion to inion and from auricle to auricle. Fp, frontal pole position; F, frontal line of electrodes; C, central line of electrodes; P, parietal line of electrodes; T, temporal line of electrodes; O, occipital line of electrodes. The outer circle was drawn at the level of the nasion and inion. The inner circle represents the temporal line of electrodes. The frontal pole and occipital electrodes are 10 per cent from the nasion and inion respectively. Twice this distance, or 20 per cent, separates the other line of electrodes. [Adapted and redrawn from Jasper (1958); used with permission of the publisher].

All IT stimuli were presented on a computer monitor at a viewing distance of approximately 0.5 m. The target figure consisted of two vertical lines 22 mm and 27 mm in length and joined at the top by a horizontal line 12 mm long. The shorter line appeared on the left or the right equiprobably. Following the exposure of the target figure it was immediately replaced by a "flash mask" (Evans & Nettelbeck, 1993; see Figure 1.1) of 290 ms duration and consisting of two vertical lines 37 mm long and both shaped as lightning bolts. The appearance of the target figure was preceded by the appearance of a small filled circle 4 mm wide in the area in which the subsequent target figure would appear; this acted as a warning cue. The duration of the warning cue was 500 ms and it was followed immediately by the target figure. When estimating IT, the subjects signalled on which side of the target figure the shorter line had appeared by pressing either the left- or right-hand button on a keypad. When recording ERPs, subjects signalled by pressing the corresponding button on a bar that rested on the arms of the chair.

All subjects completed the digit symbol (DS) subtest of the WAIS-R. Additionally, 31 subjects completed the remainder of the WAIS-R at a subsequent session. All tests were administered according to the instructions in the manual.

Procedure.

Prior to EEG recording, all subjects completed two IT estimation procedures. The average of these estimates was used to determine the SOAs used during EEG recording. The IT estimation began with familiarisation with task requirements. Subjects then performed 10 trials with an SOA of 835 ms, 10 trials with an SOA of 418 ms and 10 trials with an SOA of 250 ms. Perfect performance was required at the first two SOAs and nine correct responses were required at the latter SOA, before the IT estimation procedure began. The estimation algorithm was an adaptive staircase procedure (Wetherill & Levitt, 1965) that returned an estimate of IT at the 90% accuracy level. Subjects then completed the DS.

After preparation of the subjects for EEG recording, the presentations of trials began. The SOAs for the IT– condition were either 17, 33 or 50 ms and the SOAs for the IT+ condition were either 100, 117 or 134 ms; one pair of these was assigned to the subject on the basis of their previously determined IT estimate. For example, a subject with an IT estimate of 50 ms was presented with target figures with SOAs of 17 and 100 ms duration; a subject with an IT estimate of 120 ms encountered SOAs of 50 and 134 ms. The aim was to present trials that would be approximately equally easy or difficult for each subject, on the basis of individual estimates of IT. However, it is important to note that the subjects were unaware that only two SOAs were to be presented. In addition to these trials, another condition was employed wherein the warning cue used in the IT estimation procedure (i.e. the small filled circle) was presented by itself therefore signalling nothing and requiring no response. For this condition the subject was instructed merely to fixate the centre of the computer monitor.

First, the warning cue alone condition and then the IT– and IT+ conditions were presented. One hundred presentations of the warning cue by itself at intervals of between 1.5 and 4 s constituted the warning cue alone condition. Next, 100 presentations of each of the IT– and IT+ trials followed in random order at intervals of between 1.5 and 4 s. Presentations paused after 100 trials until the subject indicated readiness to continue.

EEG recording epochs were of 2 s duration, the sampling rate being 512 Hz. All EEG processing was done with SCAN (Neuroscan Inc.) software as follows. A 40 Hz low-pass filter (–6 dB at 40 Hz) with a slope of 24 dB/octave was applied and then a voltage baseline correction was applied to each epoch of EEG by subtracting the mean voltage over the whole epoch from each data point. Any sweep in which the EOG amplitude exceeded ±85 μV (indicating eye-blink or movement) was excluded from averaging. EEG sweeps were averaged so as to construct five ERPs: a 500 ms ERP for the cue alone condition beginning at the onset of the cue; two 500 ms ERPs beginning at the onset of the warning cue in the IT– and IT+ trials; and two 500 ms ERPs beginning at the onset of the target figure in the IT– and IT+ trials. These five ERPs will be referred to hereafter as (i) warning cue alone, (ii) warning cue IT–, (iii) warning cue IT+, (iv) target IT–, and (v) target IT+.

The string measure was calculated for the epoch 0 - 300 ms for each of the five ERPs; this corresponds to the epoch used by Bates and Eysenck (1993) and excludes the P300 deflection to the onset of the target figure, which under this paradigm has a latency of approximately 360 ms (Burns, 1993). The string measure was also calculated for the epoch 100 - 200 ms for each of the five ERPs; this is the epoch Stough et al. (1990) found to produce correlations of the greatest magnitude between the string measure and IQ. The string measure was calculated using the formula provided by Barrett and Eysenck (1992b):

$$\text{String measure} = \sum_{i=2}^{N} \frac{(V_{i-1} - V_i)^2}{N-1};$$

where V is the array of voltages defining the ERP and N is the number of sample points in the epoch. This formula calculates the string measure of D.E. Hendrickson[14] (1982).

3.2.2 Results

The mean of the average IT estimates for the 40 subjects was 81.7 ms ($SD = 14.1$); the correlation between the two estimates was .68 ($p < .001$). The mean WAIS-R scores were

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[14] The most obvious way of calculating the measure from digital data is as the sum of the absolute differences between every two successive sampling points. The formula used here weights the average of the squared differences between successive data points and thereby gives greater weight to large deviations. This formula is used here because it was the one provided by the originators of the measure and because it was the one used by Stough et al. (1990) who were the only researchers to report correlations between the string measure and IQ as high as the Hendricksons.

13.3 (*SD* = 1.9) for DS (*n* = 40); and 120.4 (*SD* = 14.5), 111.5 (*SD* = 13.3), and 118.4 (*SD* = 14.1) for VIQ, PIQ, and FSIQ respectively (*N* = 31). The distributions of the WAIS-R scores are shown in Figure 3.2. The correlation matrix for IT and the WAIS-R scores is shown in Table 3.1.

Table 3.1

Pearson correlation coefficients between IT and WAIS-R scores

	IT	DS	VIQ	PIQ
DS	–.25[a]			
VIQ	–.15	.49**		
PIQ	–.30*	.46**	.66**	
FSIQ	–.25	.53**	.93**	.88**

Note. *N* = 31; [a]*N* = 40

**p* < .05, ***p* < .01, one-tailed.

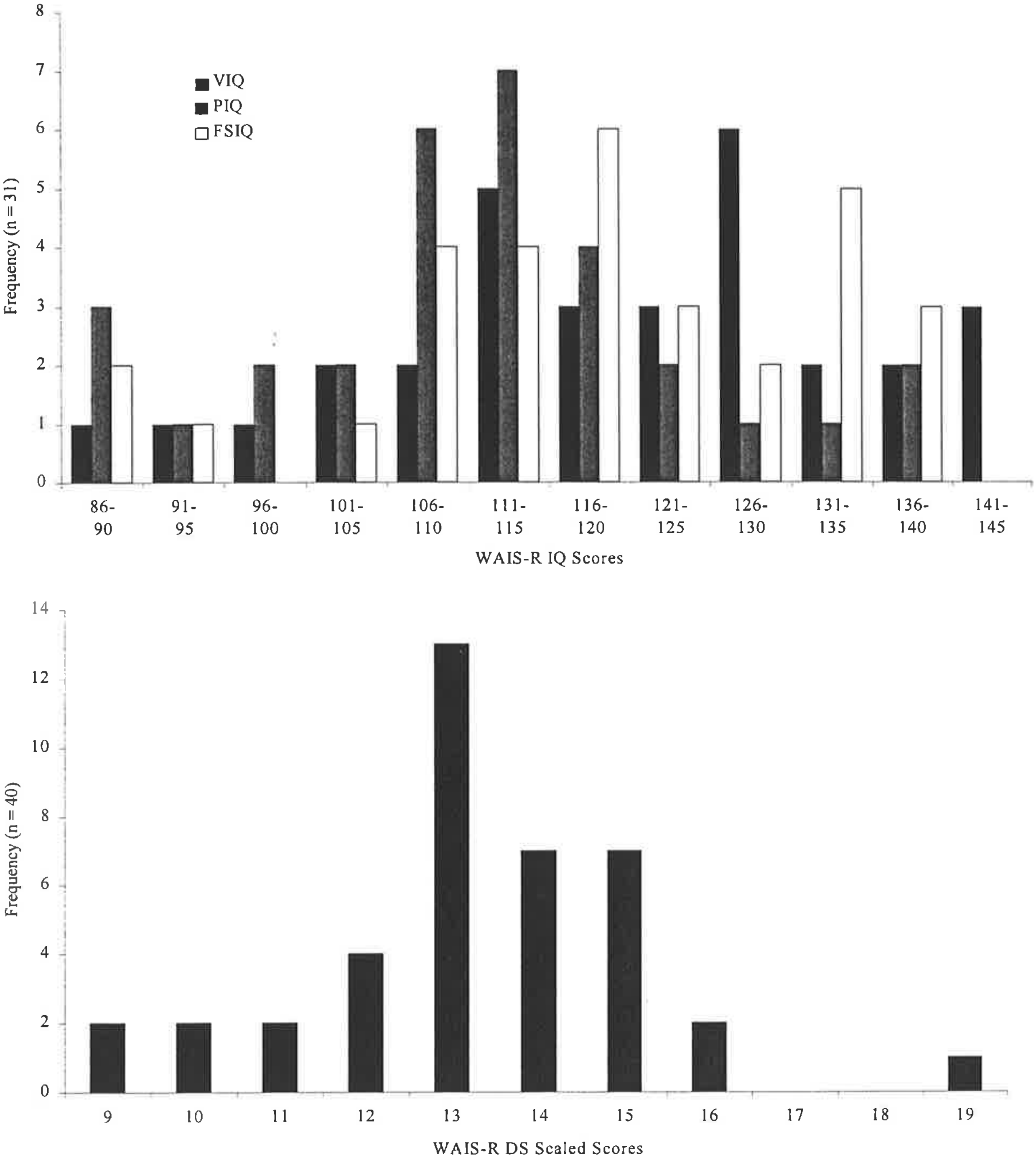

Figure 3.2. Frequency distributions for WAIS-R IQ scores ($N = 31$) and WAIS-R digit symbol (DS) subtest scaled scores ($N = 40$).

The correlations between IT and the WAIS-R scores were consistent with the finding of a modest negative correlation between IT and PIQ (Kranzler & Jensen, 1989; Nettelbeck, 1987). Similarly, the WAIS-R scores showed the usual positive manifold. This last point is important in considering the correlations of the WAIS-R scores with the string measure because not all subjects completed the full WAIS-R but all subjects completed the DS.

The correlations between the string measure and IT and WAIS-R scores are shown in Tables 3.2 and 3.3. The correlations between the string measure and IT and DS were consistent with the prediction based on the Hendricksons' theory. However, the correlations between the string measure and the full WAIS-R scores were near zero and therefore do not support either the Hendricksons' theory or Bates' theory.

The pattern of results for the epoch 100 - 200 ms (Table 3.3) is similar to that for the epoch 0 - 300 ms. Both of these epochs exclude the P300 deflection to the target stimulus; the longer epoch contains all deflections up to and including the P200, the shorter epoch centres on the P200. This finding is consistent with that of Haier et al. (1983).

3.2.3 Discussion

The results here join those described in Chapter 2 that found near zero correlations between the string measure and IQ. To the extent that support for either the Hendricksons' theory or Bates' theory can be claimed, it is clear that some part of these results are consistent with the Hendricksons' theory. This is because the experimental conditions employed here certainly required focussed attention and, according to Bates' theory, negative correlations between the string measure and IQ should have been found. Of 30 correlations between the string measure and DS, 28 were positive, two at $p < .05$ and a further three at $p < .01$.

Additionally, to be consistent with Bates' theory and findings (Bates & Eysenck, 1993), correlations between the string measure and IT should have been positive. However, of 30 correlations between the string measure and IT 28 were negative, four at $p < .05$.

Table 3.2

Pearson correlation coefficients between string measure (0 - 300 ms) from five ERP conditions at three electrode sites and IT and WAIS-R scores

ERP condition	Site	IT[a]	DS[a]	VIQ[b]	PIQ[b]	FSIQ[b]
Warning cue alone	Fz	–.30	.08	.02	–.04	–.02
	Cz	–.34*	.18	.08	–.01	.03
	Pz	–.32*	.10	.18	.00	.11
Warning cue IT–	Fz	–.06	–.06	–.27	–.24	–.29
	Cz	–.11	.15	–.12	–.17	–.16
	Pz	–.21	.10	–.10	–.12	–.13
Warning cue IT+	Fz	–.12	.14	–.21	–.14	–.22
	Cz	–.23	.24	.10	.08	.08
	Pz	–.38*	.14	.13	.08	.10
Target IT–	Fz	–.17	.42**	.17	.12	.14
	Cz	–.23	.53**	.09	.13	.09
	Pz	–.27	.07	–.04	.08	.00
Target IT+	Fz	–.28	.30	.13	.01	.06
	Cz	–.26	.38*	.06	–.07	–.01
	Pz	–.27	.24	–.10	–.10	–.13

Note. [a] $N = 40$; [b] $N = 31$

*$p < .05$, **$p < .01$, two-tailed

Table 3.3

Pearson correlation coefficients between string measure (100 - 200 ms) from five ERP conditions at three electrode sites and IT and WAIS-R scores

ERP condition	Site	IT[a]	DS[a]	VIQ[b]	PIQ[b]	FSIQ[b]
Warning cue alone	Fz	–.01	.05	.03	–.14	–.05
	Cz	–.16	.31*	.24	.07	.18
	Pz	–.30	.25	.31	.07	.21
Warning cue IT–	Fz	–.03	.00	–.30	–.24	–.31
	Cz	–.07	.19	–.03	–.08	–.06
	Pz	–.17	.14	–.03	–.07	–.06
Warning cue IT+	Fz	–.01	.28	–.14	–.12	–.16
	Cz	–.11	.23	.16	.12	.13
	Pz	–.29	.21	.08	.04	.05
Target IT–	Fz	–.27	.26	.13	.04	.09
	Cz	–.35*	.41**	.15	.18	.17
	Pz	–.13	–.01	.08	.13	.10
Target IT+	Fz	–.08	.11	–.16	–.06	–.14
	Cz	–.05	.20	–.14	.00	–.09
	Pz	–.02	.13	–.20	–.12	–..20

Note. [a] *N* = 40; [b] *N* = 31

**p* < .05, ***p* < .01, two-tailed

Questions arise as to why the results here show such variation from predictions based on either of the theories of the string measure. First, consideration is given to procedural differences between this study and that of Bates and Eysenck (1993), which may have operated to negate the effect found by them and confirmed by Bates et al. (1995). Second, consideration is given to the issue of how the string measure relates to the ERP and whether this may account for the variation in string measure findings.

Procedural Differences

The first difference between this study and Bates and Eysenck (1993) has already been noted. Here, when recording ERPs, target figures with only two SOAs were used. This is in contrast to the Bates and Eysenck study where the SOAs were controlled by an adaptive staircase procedure and varied with the performance of the subjects. If there were any latency variation within the target figure ERPs at these different SOAs[15] then this may have operated to attenuate the complexity of the ERPs when they were averaged together (Ruchkin, 1988, pp.13-15). However, this would not have affected the ERPs to the warning cue utilised in the Bates and Eysenck study and hence it is unlikely to be the factor that differentiates that study from this one.

Another procedural difference that may have operated to produce the different results relates to the warning cue and preparatory periods employed, and to the response stimulus intervals used. Firstly, in this study, the warning cue was a visual stimulus presented for 500 ms immediately prior to the appearance of the target figure. In the Bates and Eysenck (1993) study, the warning cue was a 50 ms tone combined with the lighting of a fixation point, followed by a random preparatory period of between 1 and 3 s prior to the appearance of the target figure. Secondly, in this study, varying response stimulus intervals of between 1.5 and 4 s were used whereas Bates and Eysenck employed a fixed response stimulus interval of 2 s. It is possible that the conditions employed by Bates and Eysenck have produced the

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[15] This possibility is addressed empirically in Appendix III

slow wave ERP phenomenon known as the contingent negative variation (CNV). The CNV occurs when two stimuli are paired and the second of the stimuli requires a motor response (Regan, 1989, p.217). These conditions accurately describe the Bates and Eysenck procedure but not the procedure used here, where the warning cue and target figure were temporally contiguous and no CNV was detected (although this may have been a function of the low-pass filter setting used here). It is unclear how this difference would account for the reversal of sign of correlations.

How the string measure relates to the ERP

A final possible factor that may account for the difference in results is the procedure used to calculate the string measure. Here the formula of D.E. Hendrickson (1982) has been used; this same formula was used in the two studies which have provided the strongest confirmation of the relationship predicted by the Hendricksons' theory (D.E. Hendrickson, 1982; Stough et al., 1990). Bates and Eysenck (1993) used a different procedure and Bates et al. (1995, p.34) have since advocated the adoption of that procedure. Bates' procedure involves first normalising the ERPs and then computing the string measure. While this procedure has been criticised (Barrett & Eysenck, 1994, p.17), it does overcome the problem of confounding the string measure with amplitude of the ERP. This last point leads to a consideration of what has been seen as a problem with the string measure and this is the subject of the next chapter of this thesis.

Robinson (1993) noted that "with just a little reflection one can appreciate the great weakness of the string-length index, namely, that it lacks any specificity whatsoever and is sensitive to every possible difference that might distinguish the AER ['averaged evoked response' i.e., ERP] of one person from that of another" (p.705). Robinson also pointed out that it was important to specify which aspects of the ERP contributed to differences in the string measure under any experimental paradigm. As Bates et al. (1995) noted, it is clear that amplitude is one factor that contributes to the string measure and hence they have adopted a procedure that controls for amplitude. However, other research has suggested that amplitude of the ERP is the factor that has determined the correlation between the string measure and IQ (e.g., Haier et al., 1983). On the other hand, Stough et al. (1990) reported that amplitude within an epoch that produced high string measure correlations with IQ showed no correlation with IQ.

When these contradictory findings were considered, along with evidence that Barrett and Eysenck (1992b) reported, of the attenuation of string measure correlations with IQ by the application of low-pass filtering (see Chapter 2), it seemed that Robinson's position merited investigation. That is, what is it within ERPs that determines the magnitude of the string measure? Does this factor (or factors) bear any consistent relationship with IQ? In an attempt to answer these questions a review of literature on relationships of ERP amplitude with IQ was undertaken. Further, a review of studies that had interrogated the frequency content of ERPs in relation to IQ was undertaken. These reviews and the development of a model of the relationship of string measure magnitude to the frequency content of the ERP, constitute Chapter 4 of this thesis.

Chapter Four: The string measure of the ERP–what does it measure?[16]

4.1 Introduction

As noted in Chapter 3, Robinson (1993) has criticised the string measure on the basis of its nonspecificity. That is, he insisted the measure is of little use either practically or theoretically because it is sensitive to any and all differences between the ERPs of different individuals. Others have made similar criticisms; Andreassi (1995, p.97) pointed to the reliance of the string measure on ERP amplitude, which can be influenced by, for example, skull thickness or the placement of the reference electrode (Nunez, 1990).

Bates (Bates & Eysenck, 1993; Bates et al., 1995) has taken the position that the effects of ERP amplitude must be controlled for when calculating the string measure and achieves this by normalising the ERP "to a standard range of ± 1" (Bates et al., 1995, p.34). Widaman et al. (1993, p.209), in their description of the method that they used for calculating the string measure, also pointed to the desirability that "high frequency noise" be removed from their ERPs. However, given the uncertainty as to what aspects of the ERP are indexed by the string measure this approach may be premature. Haier et al. (1983), for example, concluded that the string measure was dependent on the amplitude of the N140-P200 complex of their visual ERPs. Stough et al. (1990), by contrast, reported a correlation of .71 ($p < .01$) between the string measure of an epoch 100-200 ms post-stimulus and IQ but found no relationship between N140-P200 amplitude and IQ. Since the N140-P200 complex would lie within the epoch for which the string measure was calculated, a positive correlation between the amplitude measure and IQ would be expected. Stough et al. (1990) did not report whether the string and amplitude measures were intercorrelated.

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[16] The material in this chapter has appeared, in somewhat different form, as Burns, N.R., Nettelbeck, T. & Cooper, C.J. (1997). The string measure of the ERP: What does it measure? *International Journal of Psychophysiology, 27,* 43-53.

Evidence from the literature on the relationship between ERP amplitude and IQ may serve to resolve the contradictions noted in the literature on the string measure and IQ. Further, there is suggestive evidence as to the effect of various low pass digital filters on the string measure. Barrett and Eysenck (1992b), for example, reported correlational data for ERPs both prior to and after digital filtering—low-pass filter (–21 dB at 40 Hz). Correlations between the string measure (Cz referred to the left mastoid) and VIQ, PIQ and FSIQ prior to filtering were –.37, –.49, and –.44, respectively; these correlations were reduced to –.16, –.22, and –.19, respectively, after the application of the low-pass filter (as discussed in Chapter 2). Thus, removing the high frequency content of the ERP decreased the magnitude of the correlations between the string measure and IQ. This suggests that the string measure is sensitive to the high frequency content of the ERP.

Moreover, given the possibility of a relationship between high frequency ERP content and IQ, then valuable information may be lost by the removal of the high frequency content. Certainly, evoked gamma band (i.e., > 20 Hz) activity is of current research interest in cognitive psychophysiology (e.g., Pulvermeuller et al., 1994; Sheer, 1989); and Crick (1994, pp.244-46) has speculated about the role of such high frequency activity in the genesis of consciousness.

This chapter reviews the relevant literature in an attempt to account for the inconsistencies noted in the relationship of the string measure with IQ. Firstly, the literature on the relationship of ERP amplitude with IQ is reviewed. Secondly, the literature on the frequency content of the ERP and IQ is reviewed.

4.2 ERP amplitude and IQ

To pursue the details of individual studies in the course of this review, as was done with the string measure studies, will burden the reader unnecessarily. This review will therefore be presented in summary form.

Table 4.1 summarises studies that have found a positive relationship between IQ and some amplitude measure of the ERP (Caryl, 1994; Galbraith, Gliddon & Busk, 1970; Haier et al., 1983; Hendrickson & Hendrickson, 1980; Josiassen, Shagass, Roemer & Slepner, 1988; Lelord, Laffont & Jusseaume, 1976; Pelosi et al., 1992a, 1992b; Perini et al., 1989; Rhodes et al., 1969; Robinson et al., 1984; Rust, 1975; Sandman & Barron, 1986; Shagass et al., 1981; Shucard & Callaway, 1974; Stough et al., 1990; Zhang et al., 1989b). Table 4.2 summarises studies that have found a negative relationship between IQ and some amplitude measure of the ERP (Barrett & Eysenck, 1992b, 1994; Daruna & Karrer, 1984; Egan et al., 1995; Federico, 1984; Gasser, Pietz, Schellberg & Kohler, 1988; McGarry-Roberts, Stelmack & Campbell, 1992; Tan, Akgun, Komsuoglu & Telatar, 1993; Vogel et al., 1987; Widaman et al., 1993). Not included in this review were several studies reviewed by Straumanis and Shagass (1976); these studies have not been included here because they were concerned with clinical populations of, mainly, very young children and therefore their generalisability is questionable.

Table 4.1

Studies reporting a positive relationship between ERP amplitude and IQ

Study	N	Amplitude Measure(s)	Statistic	Comments
Rhodes et al. (1969)	40	Peak-to-peak; peaks 0-300 ms	ANOVA ('bright vs dull')	$p <. 05$
Galbraith et al. (1970)	40	Ratios of peak-to-peak amplitudes of late positive component (LPC)	None	
Shucard & Callaway (1974)	16	Mean amplitude; 0-500 ms	ANOVA ('bright vs dull')	$p < .05$; non-attending conditions only
Rust (1975)	296	Peak-to-peak amplitude; P2, N2, P3	Pearson r	ns
Lelord et al. (1976)	34	Peak-to-peak; peaks 0-500 ms	Multiple t tests	'normals' vs IQ 50-60 vs IQ 20-50 $p <.02$
Hendrickson & Hendrickson (1980)	93	Not specified	Pearson r	22 of 45 correlations $p <.05$
Shagass et al. (1981)	100	Mean amplitudes of overlapping epochs	ANOVA ('low IQ vs high IQ')	$p < .1$; VERPs only
Haier et al. (1983)	22	Baseline-to-peak; P100, P200 Peak-to-peak; N140-P200	Pearson r	$p < .05$
Robinson et al. (1984)	15	Baseline-to-peak; P100, P200 Peak-to-peak; N140-P200	Pearson r	$p < .05$
Sandman & Barron (1986)	39	Peak-to-peak; P1, N1, P2, N2	Pearson r	$p < .05$ for P2
Josiassen et al. (1988)	57	Mean amplitudes of overlapping epochs	ANOVA (three groups) Pearson r	$p < .05$
Zhang et al. (1989b)	35	Baseline-to-peak; P200, P300	Pearson r	ns
Perini et al. (1989)	47	Baseline-to-peak; P300	t test (controls vs patients)	$p < .001$
Stough et al. (1990)	20	Peak-to-peak amplitude; N140-P200	Pearson r	
Pelosi et al. (1992a)	19	Ratio of baseline-to-peak; P400 (between conditions)	Pearson r	$p < .001$
Pelosi et al. (1992b)	19	Baseline-to-peak; P250, N290, P400	Pearson r	$p < .01$
Caryl (1994)	35	Amplitude from baseline at a timepoint Baseline-to-peak; N140, P200, N240, P300	Pearson r	ns

Table 4.2

Studies reporting a negative relationship between ERP amplitude and IQ

Study	N	Amplitude Measure(s)	Statistic	Comments
Shucard & Horn (1973)	94	Sum of peak-to-peak amplitudes; 500 ms epoch	Pearson *r*	High IQ group had lower amplitude in non-attending condition
Daruna & Karrer (1984)	24	Baseline-to-peak; N1, P2, P3, Slow Wave	Stepwise regression	Low IQ subjects had greater N1 amplitude
Federico (1984)	50	Root mean square amplitude; 533 ms epoch	Canonical correlation Pearson r	$p <.05$
Vogel et al. (1987)	236	Oscillation measure of combined amplitudes	Pearson *r*	ns; no correlations > -.1
Gasser et al. (1988)	56	Baseline-to-peak; all peaks to 300 ms	Rank correlation	
Barrett & Eysenck (1992b)	40	Mean absolute amplitude; 256 and 512 ms epochs	Pearson *r*	
McGarry-Roberts et al. (1992)	30	Baseline-to-peak; P300	Pearson *r*	ns; 1 of 6 $p <.01$
Tan et al (1993)	7	Peak-to-peak; N1-P1 Area under N1-P1 complex	Pearson *r*	
Widaman et al. (1993)	48	Peak-to-peak; P1-N1, N1-P2, P2-N2	Pearson *r*	21 $p <.05$; 71 of 81 correlations were negative
Barrett & Eysenck (1994)	200	Mean absolute amplitude; 256 and 512 ms epochs	Pearson *r*	
Egan et al. (1995)	50	Baseline-to-peak; N100, P200, P300	Pearson *r*	ns; 2 of 9 $p <.05$

Table 4.1 lists 16 studies with a total number of 927 subjects, the median number of subjects per study being 35. Table 4.2 lists 11 studies with a total number of 835 subjects, the median number of subjects per study being 50. This review suggests that the nature of any relationship between ERP amplitude measures and IQ is at least ambiguous. While it could be argued that methodological differences between studies account for the inconsistency in these correlations between ERP amplitude measures and IQ, these differences are not based on whether sensory (Barrett and Eysenck, 1992b, 1994; Federico, 1984; Galbraith et al., 1970; Gasser et al., 1988; Haier et al., 1983; Hendrickson and Hendrickson, 1980; Josiassen et al., 1988; Lelord et al., 1976; Rhodes et al., 1969; Robinson et al., 1984; Rust, 1975; Sandman and Barron, 1986; Shagass et al., 1981; Shucard and Callaway, 1974; Stough et al., 1990; Tan et al., 1993; Vogel et al., 1987; Widaman et al., 1993) or task-related (Caryl, 1994; Daruna and Karrer, 1984; Egan et al., 1995; McGarry-Roberts et al., 1992; Pelosi et al., 1992a, 1992b; Perini et al., 1989; Zhang et al., 1989b) ERPs were recorded. Large and small scale studies employing various stimulus modalities and recording montages have found significant relationships suggesting that high IQ is associated with large amplitude ERPs; but similar studies have also found low IQ to be associated with large amplitude ERPs. Other studies have found no significant relationship between IQ and ERP amplitude. Given the total numbers of subjects involved and the fact that the median sample sizes of the two groups of studies are similar, it is unlikely that these inconsistent findings are a statistical artefact. The possible confounding factors that can affect scalp recorded amplitude measures would add to error variance and thereby increase the possibility of Type II error. While it is difficult to see how this would reverse any effect that might exist, the inconsistency in the pattern is relationships is not surprising.

The inconsistency in the relationship of the string measure with IQ is explicable if the string measure is determined to any great extent by the amplitude of the ERP. This follows logically as a conclusion of the review, presented above, which finds no reliable relationship between ERP amplitude and IQ. However, other characteristics of the ERP may contribute to the determination of the string measure; and such characteristics may also be related to IQ. It has been suggested above that the high frequency content of the ERP may be such a factor.

4.3 Fourier analyses of ERPs and IQ

Consideration is now given to the results of studies that have employed Fourier analysis of the ERP in an effort to understand the relationship between the ERP and IQ. Seven studies are considered in this review. The most recent of these studies was published in 1980. The purpose of this exposition is to question whether any relationship exists between the higher frequency content of the ERP and IQ.

As was noted in Chapter 1 the issue arises how the Fourier analysis of an ERP can be interpreted. The ERP derives its major theoretical and practical value from its excellent temporal resolution (Regan, 1989). Fourier analysis is a transformation that expresses waveform data (in the time domain) as a sum of the power of sine waves of certain frequencies. The expressions of these data are equivalent—no information is lost. But, the data are expressed differently and, in the case of the ERP, the data are removed from the domain where their greatest strength lies. Nevertheless, the Fourier transformation of the ERP, because it is a mathematically equivalent expression of the data, can provide information pertinent to the question of what the string measure measures. This follows from the fact that the string measure comprehensively treats the ERP as an entity in itself (as contrasted to any amplitude measure which can only be a partial descriptor). Given this, the discussion now turns to the studies under consideration.

Bennett (1968) reported a study of 36 subjects in *Nature*. Therefore, no details of the subjects, the IQ testing or the EEG recording were given, save that the stimuli were visual and that the EEG was recorded from over the occipital cortex. Nevertheless, the range of IQ scores can be determined from the published scatter diagram and was approximately 77-146. The dependent variable was described as 'the natural frequency of the dominant function'. This measure, derived from the Fourier analysis, was based on the work of Freeman (1964) and in this instance appears to be identical with the spectral frequency at which power was maximal. The correlation between this measure and IQ was .593 (significance not stated but $p < .01$, for a sample of this size). This means that higher IQ subjects had ERPs with a higher proportion of high frequency content than did the lower IQ subjects.

Weinberg (1969) reported a study of 42 subjects (age range, 18 to 39 years). Subjects completed VIQ scale from the WAIS and scores ranged between 77-146. EEG was recorded from montages over the occipital cortex and stimuli were 20 ms light flashes. Intensity was 10^5 lumens and subjects had eyes closed. Three separate sets of correlations were reported. The first was the correlation with 'overall amount of activity'—this was positively related to IQ. The second correlation reported was between variability in the different amounts of activity in each frequency band and IQ—again there was a positive relationship. The third correlations were between the spectral components and IQ. The Fourier analysis was performed on 500 ms epochs of ERP at 2 Hz resolution. The highest correlations were between IQ and activity in the range 10-14 Hz; (because eyes were closed, α-activity would have been optimally prevalent). Weinberg summarised his results as follows: "there are striking differences in frequencies within traces of the six highest (146-140) and six lowest (77-120)[17] IQ subjects. Low IQ subjects tend to show predominantly low frequency activity, especially with respect to early components of the AER ... generally, increases in IQ seem to be inversely related to the amount of low frequency activity" (p.814).

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[17] It is obvious that the term 'low' is misapplied here.

Taken together, these results support the notion that higher IQ is associated with ERPs that have higher amounts of higher frequency components.

Ertl published two papers (1971, 1973) concerned with the Fourier analysis of ERPs and relationships with IQ. Both papers reported analyses of the same data. These data were culled from an FM tape library of more than 1000 subjects. The selection criteria were that "they had IQ scores of over 120 on two out of three of the Otis, PMA and WISC IQ test" or "they had IQ scores of less than 85 on two out of three IQ tests" (Ertl, 1971, p. 525). The analyses were thus based on two groups with markedly disparate IQs, combined to provide a sample of 164 children with a mean age of 11.6 years. The EEG recording was from a montage with electrodes 6 cm apart astride C4; stimuli were light flashes. The first paper reported results of Fourier analysis of two epochs; 500 ms post-stimulus and 250 ms post-stimulus with 2 Hz and 1 Hz resolution respectively. Ertl reported finding no significant differences between the two groups but noted that "there is some indication that high IQ subjects tend to have higher frequency components in the first 200 ms after stimulation" (1971, p.525). The second paper (1973) applied a different methodology for the Fourier analysis, using "an 80 ms time window which was incremented in 8 ms steps from 40-200 ms" (p.209). This methodology had the advantage of focussing on smaller epochs of the ERP—Ertl was particularly interested in the first 150 ms of the ERP; see, for example, Chalke and Ertl (1965); Ertl and Schaffer (1969). However, it also had the disadvantage of only resolving the frequency spectrum from 12 Hz upwards. Ertl (p.210) found, firstly, that the group of high IQ subjects had "significantly more energy content in the frequency band of 18-29 Hz at 88 to 136 ms following the stimulus" and, secondly, that wherever a significant difference between the two groups was found "the high IQ subjects always had more energy content than low IQ subjects".

Shucard and Callaway (1973) reanalysed data (Shucard & Horn, 1972) in which a significant negative correlation between ERP latency and IQ had been found. There were 107 subjects, the EEG montage was F4-P4 and F3-P3 and stimuli were light flashes. The ERPs were Fourier analysed and "peak frequency, power at peak frequency and power at 14.04 Hz were determined" (p.148). No significant relationships were found with IQ but there was "a tendency for power at 14.04 Hz to correlate positively with intelligence" (p.148).

The study by Flinn, Kirsch and Flinn (1977) will be dealt with in some detail as it raised several issues pertinent to the current discussion. These researchers were mainly concerned with the question of whether ERP correlations with intelligence were the result of differences between only the lowest IQ subjects and the rest of the population or whether such differences were found across the full range of IQ. Subjects were 64 eleven year olds; IQ scores ranged from below 80 to above 130, with approximately equal numbers of children within each IQ band of 10 points range. EEG recording was with electrodes 6 cm apart astride C4 and stimuli were light flashes (the same recording montage and stimuli used by Ertl). Several measures were derived from the Fourier analysis of the ERPs as follows: the amplitude at different frequency bands of 6 Hz width; the average amplitude above and below a given "splitting" frequency; the bandwidth; the frequency at which the maximum spectral amplitude occurred; and the average amplitude in various frequency bands for the first 200 ms of the ERP. The results of these analyses were summarised by Flinn et al. as follows: "low IQ subjects had more power at the low frequencies and the high IQ subjects had more power at the high frequencies, as well as a broader distribution of power with frequency ... at low frequencies (less than 12 Hz), all the IQ groups had the same maximum spectral amplitude, except for the lowest IQ group ... at high frequencies, the spectral amplitudes increased steadily with increasing IQ" (p.13). The median correlation between maximum amplitude within the 6 Hz bands above 30 Hz and IQ was .37 ($p < .01$) and the correlation of bandwidth with IQ was .30 ($p < .05$). This means that the higher IQ subjects had more higher frequency content within their ERPs than the lower IQ subjects had.

The most recent of this group of studies (Osaka & Osaka, 1980) compared the ERPs of eight normal (Suzuki-Binet IQs 110-130) and eight mentally retarded (Suzuki-Binet IQs 54-76) children (age range, 12-13 years). EEG was recorded from over the occipital cortex and referred to the earlobe. Fourier analysis of 500 ms of evoked potential at 2 Hz resolution was carried out. No statistical analyses were reported but the averaged frequency spectrum of the normals had a peak at 12 Hz that was absent in the averaged frequency spectrum of the mentally retarded subjects. This finding was thus consistent with the findings of Weinberg (1969) and Shucard and Callaway (1973).

In summary, two of the seven studies (Ertl, 1973; Flinn et al., 1977) found highest correlations with IQ at frequencies of 30 Hz and above, suggesting that high frequency event-related activity may be positively correlated with IQ; a suggestion not contradicted by the other studies reviewed. If this high frequency activity can be demonstrated to be related to the string measure then this will provide evidence of the confounding of the string measure with this activity and raise further doubts as to the interpretability and hence usefulness of the string measure.

4.4 A model of the interrelationships between ERP string measure, ERP amplitude, ERP spectral power and IQ

Consideration of the preceding evidence with respect to ERP amplitude, ERP frequency content, ERP string measure and IQ has suggested a model of the interrelationships between these measures; this model is shown in Figure 4.1. Note that the model proposes that ERP amplitude measures and the ERP string measure are unreliable correlates of IQ. This unreliability arises in the case of the string measure possibly because of its dependence on ERP amplitude; amplitude measures themselves are unreliable correlates of IQ because of their relationship with factors such as skull thickness and electrode placement. Further, it is proposed that the string measure is sensitive to the high frequency content of the ERP; this high frequency content is possibly related to IQ. The lower frequency content within the ERP is of greater amplitude than the higher frequency content and therefore contributes most to the ERP amplitude measures.

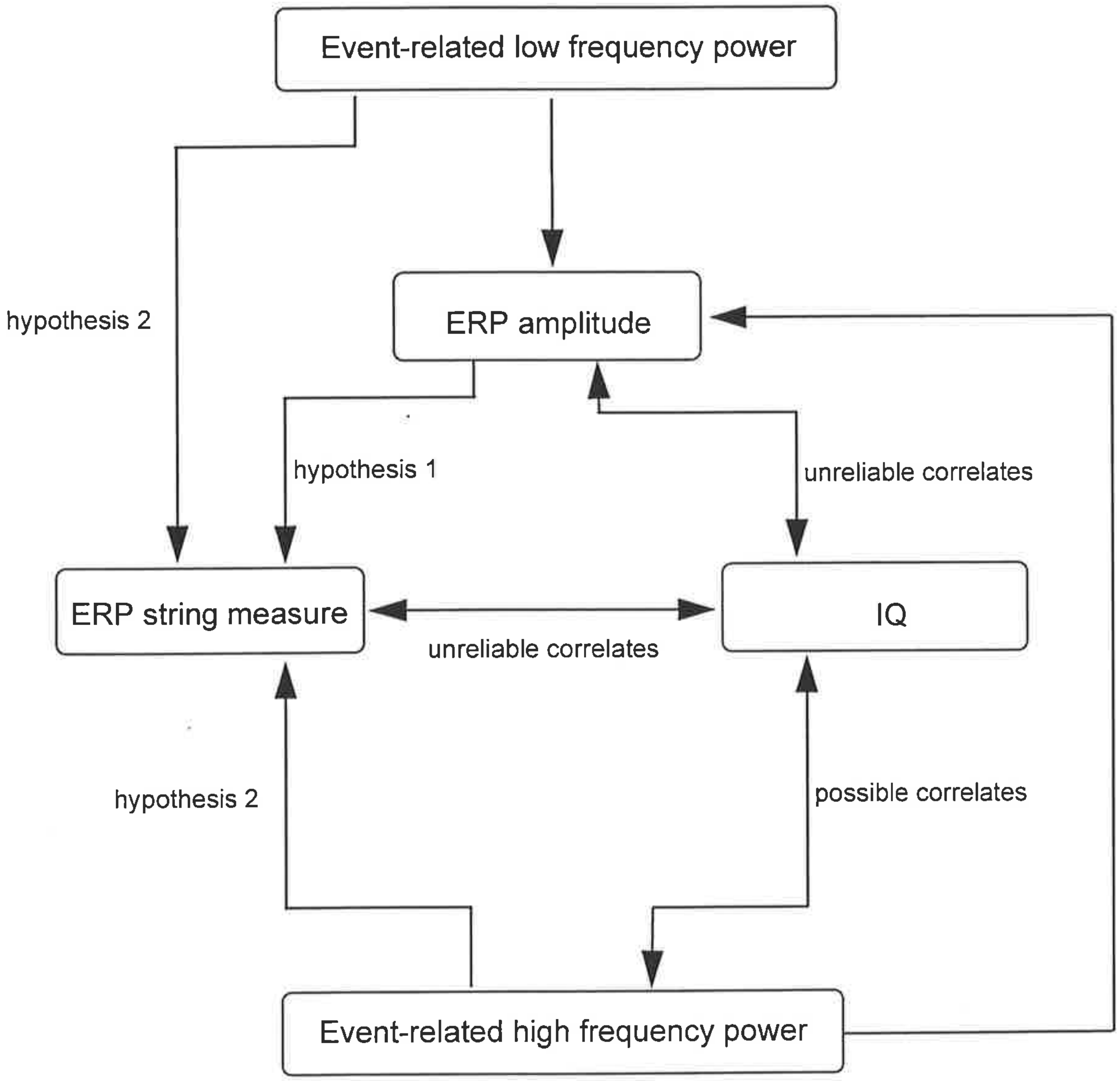

Figure 4.1. Model of the interrelationships between event-related potential (ERP) string measure, ERP amplitude, ERP spectral power and IQ.

The research reported here sought to establish the sensitivities of the string measure to the amplitude of the ERP and to the frequency content of the ERP. To this end ERPs were constructed from the EEG data recorded for the experiment reported in Chapter 3. From these ERPs both component and absolute amplitude measures, and the string measure were calculated. Further, the power spectra of the ERPs were calculated by Fourier analysis. (The appropriateness or otherwise of describing ERPs by their spectral composition has been discussed above. However, in the context of the study reported here, the spectral description is appropriate because the aim of the study is to test the sensitivities of the string measure to the various components that constitute the ERP waveform. The time domain description and the frequency domain description contain exactly the same information (Brigham, 1974, pp.1-8) but the quantification of the information is more readily achieved in the frequency domain).

Hypotheses derived from the model shown in Figure 4.1 and tested here are as follows.

Hypothesis 1. The string measure of the ERP and amplitude measures of the ERP are positively correlated.

Hypothesis 2. The string measure of the ERP indexes event-related activity across the power spectrum from low to high frequencies.

Support for these hypotheses would mean that the string measure is an inappropriate measure to apply to ERP data. This conclusion would be consistent with the fact that only three studies using the measure have reported moderately high correlations between the measure and IQ (but one of these was in the opposite direction to the other two) whereas the remaining studies using the measure have reported at best modest but more often near-zero correlations with IQ.

4.5 Method

The rationale for the experimental paradigm and the experimental details have been detailed in Chapter 3. Details of EEG processing differed from those described there and were as follows.

EEG recording epochs were 2 seconds in duration, with a sampling rate of 512 Hz. All EEG processing was done with SCAN (Neuroscan Inc.) software as follows. A 40 Hz low-pass filter (–6 dB at 40 Hz) with a slope of 24 dB/octave was applied and then a voltage baseline correction was applied to each epoch of EEG by subtracting the mean voltage over the whole epoch from each datum point. Any sweep in which the EOG amplitude exceeded ±85 μV (indicating eye-blink or movement) was excluded from averaging. EEG sweeps were averaged so as to construct three ERPs: a 500 ms ERP for the cue-alone condition beginning at the onset of the cue; a 500 ms ERP beginning at the onset of the warning cue in the IT trials; and a 500 ms ERP beginning at the onset of the IT stimulus in the IT trials. (For the two measures from the IT condition (see Chapter 2, above), the EEG epochs recorded to the two different durations of IT stimuli were averaged together). These three ERPs are referred to hereafter as the cue-alone ERP, IT-warning cue ERP and IT-stimulus ERP respectively.

4.6 Results

4.6.1 ERP parameters

Figure 4.2 shows the grand average ERPs; in each case stimulus onset is at 0 ms. The P200 peak is marked in each figure; additionally, the P300 peak is indicated in the IT-stimulus ERPs.

The string measure.

The string measure was calculated for 500 ms ERP epochs; the formula used for calculating the string measure was that provided by Barrett and Eysenck (1992b) which calculates the string measure of D.E. Hendrickson (1982) as follows,

$$\text{String measure} = \sum_{i=2}^{N} \frac{(V_{i-1} - V_i)^2}{N-1};$$

where V is the array of voltages defining the ERP and N is the number of sample points in the epoch.

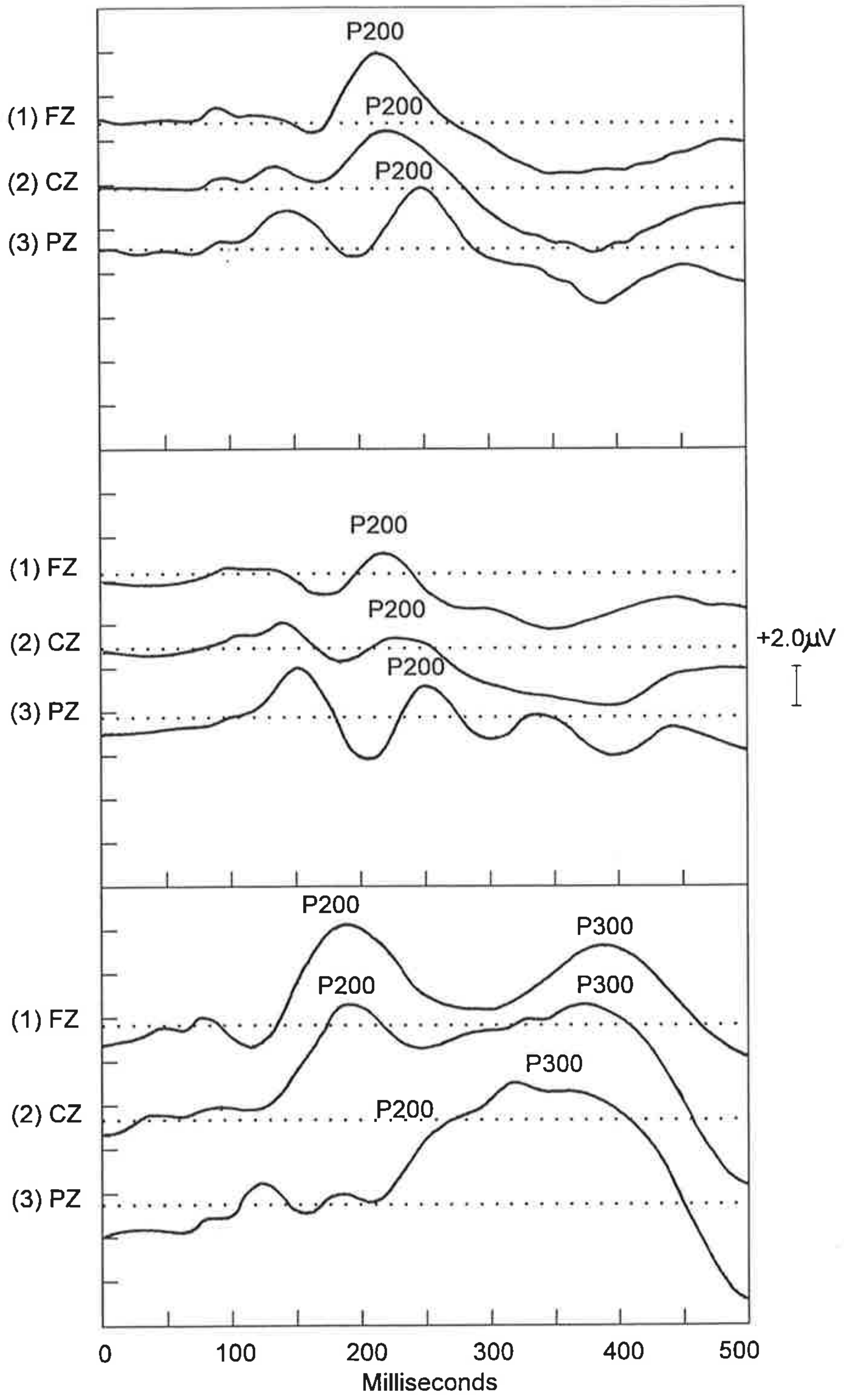

Figure. 4.2. Grand average event-related potentials (ERPs) from 40 subjects at three electrode sites for three conditions. Stimulus onset is a 0 ms. Top, cue-alone ERPs; Middle, IT-warning cue ERPs; Bottom, IT-stimulus ERPs.

ERP component amplitudes.

For the purposes of testing the hypotheses with respect to ERP component amplitudes the P200 and P300 baseline-to-peak amplitudes were measured using an automatic peak detection program; all peak identifications were visually confirmed. There was no P300 in the cue-alone and IT-warning cue ERPs. These peaks were chosen for analysis because the P200 is the major peak in the flash-stimulus visual event-related potential (Allison, 1984), and the P300 is the best studied of the so-called cognitive ERP peaks (Hillyard and Picton, 1987; Gevins and Cutillo, 1986).

Absolute ERP amplitude.

In addition to the peak amplitudes, a measure of the mean absolute amplitude of the 500 ms ERP epochs was calculated; the formula used for calculating the absolute amplitude measure was that provided by Barrett and Eysenck (1992b) as follows,[18]

$$\text{Absolute amplitude} = \frac{\sum_{i}^{N} |V_i|}{N},$$

where V is the array of voltages defining the ERP and N is the number of sample points in the epoch.

Fourier Analysis.

The Fourier analysis was accomplished by SCAN software using a standard Fast Fourier Transform algorithm; a 10% length cosine window was used to control spectral leakage. The effectiveness of this latter procedure was assessed by examining the intercorrelations of the powers within each of the bands and no evidence of consistent

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[18] It should be noted that this formula does not return the intuitively obvious digital calculation of the string measure referred to in the note in Chapter 3. Rather, this calculation provides a global amplitude estimate for each ERP.

intercorrelation was found. The power spectra were computed for the 500 ms ERP epochs from 2-256 Hz at 2 Hz resolution but only the portion up to 40 Hz was retained for the analyses. Figure 4.3 shows the power spectra of the ERPs.

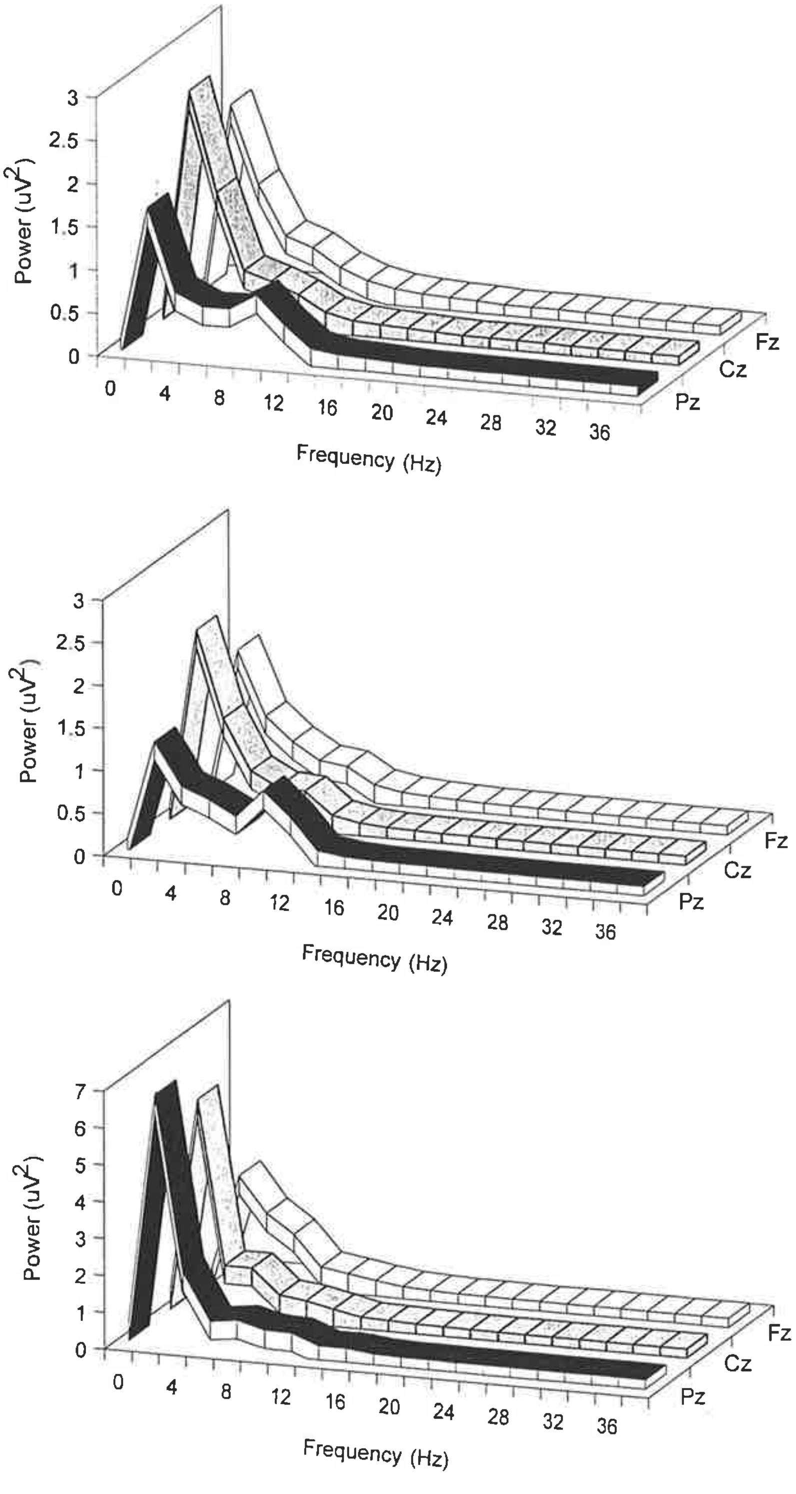

Figure 4.3. Grand average power spectra of event-related potentials (ERPs) from 40 subjects at three electrode sites for three conditions. Top, cue-alone ERPs; Middle, IT-warning cue ERPs; Bottom, IT-stimulus ERPs.

4.6.2 Hypothesis 1. ERP string measure and ERP amplitude measures are positively related.

For this and subsequent analyses, data from all electrode sites for each of the three conditions were tested. However, the outcomes were very similar and so only the results from electrode site Cz in the IT-stimulus ERP condition are presented here. (These data are summarised in overall average ERP (2) in the bottom section of Figure 4.2). The results from the other electrodes and conditions are presented in Appendix 1.

The correlations between the string measure and the P200 and P300 baseline-to-peak amplitude measures were .43 and .50 ($p < .01$), respectively. This result is in accord with the prediction and is consistent with Haier et al. (1983) who reported a mean correlation of .77 ($p < .01$) between P200 amplitude and the string measure of 508 ms ERP epochs.

The correlation between the string measure and the absolute amplitude measure of the 500 ms epoch was .52 ($p < .01$). Together, these finding support hypothesis 1, that the string measure is dependent on the amplitude of the ERP. As noted above, this dependence on ERP amplitude limits the utility of the string measure.

4.6.3 Hypothesis 2. The string measure of the ERP indexes event-related power across the full spectrum from low to high frequencies.

To test this hypothesis the ERP frequency spectra were collapsed into the traditional bands employed in EEG/ERP research, *viz.*, delta, theta, alpha and beta. The delta band was from 2 Hz up to 4 Hz; the theta band was frequencies above 4 Hz up to 8 Hz; the alpha band was frequencies above 8 Hz up to 14 Hz; and the beta band was frequencies above 14 Hz.

The correlations between the string measure of the 500 ms epoch and the power within each of the frequency bands (delta, theta, alpha and beta) were .36 ($p < .05$), .42, .75, and .68 (all $p < .01$), respectively. Hypothesis 2 is therefore supported, as is Robinson's

(1993, p.705) claim “that it is clear that the string-length will confound AER frequency and amplitude differences”.

4.6.4 Multiple regression analysis.

To further explicate the relationship of the string measure of the ERP to the Fourier analysis of the ERP, a hierarchical multiple regression procedure was employed with the string measure as the dependent variable and the band power measures entered into the regression in the order of their absolute powers; that is, delta at step 1, theta at step 2, alpha at step 3, and beta at step 4. Additionally, the absolute amplitude measure of the 500 ms epoch was entered as the final step of the regression procedure, in order to assess whether any significant additional variance in the string measure could be explained. Evaluation of the data as to their suitability for submission to these procedures (that is, testing for normality, linearity and homoscedasticity of residuals and for the presence of univariate and multivariate outliers) was undertaken. No data transformations or elimination of data were considered warranted. Table 4.3 shows the coefficient of determination (R^2) at each step of the regression procedure and the change in R^2 at each step. It can be seen that the spectral power description of the ERP accounts for 85% of the variance in the string measure, with power in each band making a significant contribution; further, the ERP amplitude measure adds no information beyond that of the spectral description of the ERP. This finding provides support for the set of interrelationships between ERP measures shown in Figure 4.1.

Table 4.3

Coefficients of determination (R^2) and change in R^2 for hierarchical multiple regression of ERP spectral bandpower and ERP absolute amplitude onto ERP string measure (electrode site Cz in IT-stimulus ERP)

Variable entered at step	R^2	Change in R^2
1. Delta (2 Hz up to 4 Hz)	.13	.13*
2. Theta (4 Hz up to 8 Hz)	.23	.10*
3. Alpha (8 Hz up to 14 Hz)	.64	.41***
4. Beta (above 14 Hz)	.85	.21***
5. Absolute amplitude	.86	.01

*$p < .05$, ***$p < .001$, two-tailed

4.7 Discussion

The impetus for undertaking this analysis was to test Robinson's recent claim, with respect to the string measure, that it confounds ERP frequency and amplitude differences (Robinson, 1993, p.705). The above analysis has shown that not only is the string measure dependent on the amplitude of the ERP but it is also dependent on the higher frequency activity within the ERP. This finding is consistent with but not identical to the claim of Barrett and Eysenck (1994, p.17) that "the string measure is actually a confounded amplitude measure, the confounding being due to noise/jitter present on the envelope of the AEP". Barrett and Eysenck applied moderately severe digital low-pass filtering to their ERPs and this had the effect of reducing the correlations between IQ and the ERP string measure because the magnitude of the string measure was reduced. The above analysis plausibly explains this finding, suggesting that the removal of the high frequency activity eliminated a part of the event-related activity that was contributing to their correlations between the string measure and IQ.

The issue of the dependence of the string measure on ERP amplitude is one which may be resolved by normalising the ERP (Bates et al., 1995; but see Barrett and Eysenck, 1994). Alternatively, where an experimental paradigm employs more than one condition (e.g., attended versus nonattended stimuli) then difference waveforms or ratios of peak amplitudes may be employed to control for differences in ERP amplitude arising from anatomical or technical (e.g., interelectrode impedance) differences between subjects or experimental sessions. The problem with these latter approaches though is that there is no theory to sustain the relationships being investigated; the Hendricksons, for example, made no mention of ERP amplitude in their exposition. Bates' attentional theory of the string measure on the other hand arises *sui generis* but assumes that the measure itself is a valid one.

The utilisation of Fourier analysis for the spectral description of the ERP has allowed conclusions to be drawn regarding the string measure and ERP amplitude. Other researchers have used this approach to investigate the relationship between the ERP and IQ (Bennett, 1968; Ertl, 1971, 1973; Flinn et al., 1977; Osaka & Osaka, 1980; Shucard & Callaway, 1973; Weinberg, 1969). The results of these studies were inconsistent but, as noted in section 4.3, above, there is a suggestion that higher frequency event-related activity is positively related to IQ. It may be time for a return to this approach; however, there is no relevant theory to guide such research. The Fourier analysis of the ERP provides a description of brain response but, as Regan (1989, p.58) notes, the value of Fourier analysis "presumably lies more in its mathematical convenience than its physiological plausibility". If spectral analyses of ERPs were found to be consistently related to IQ then at least those parts of the ERP relevant to individual differences in IQ could be identified for further study.

The conclusion drawn here about research into the relationship between brain structure and function and intelligence is that the string measure is nonspecific and consequently not useful in pursuing an understanding of the processes underlying that relationship. As Detterman (1994, pp.36) recently put it “a complex human characteristic like intelligence and a complex biological structure like the brain are not going to converge easily”. As has been seen, the string measure integrates changes in brain electrical activity in a global way and it should therefore be jettisoned.

4.8 Implications and summary

The results reported in this Chapter have implications for Bates’ (1993; Bates et al., 1995) theory. They also bear on recent research reported by Stough et al. (1995). This is because the results reported here suggest that the string measure is not a valid measure of the ERP. Bates’ theory assumes that the string measure is a valid measure of the ERP. Stough et al. claimed that the string measure is a measure of biological intelligence.

As described in Chapter 3, Bates et al. (1995) claimed support for their attentional model of the string measure on the basis of significant interactions between IQ and attention on string measure at ‘several’ of 19 electrode sites in their experiment. They then calculated a difference between string measures in their attended versus non-attended conditions. The correlation between this ‘string difference measure’ and IQ was significant at 10 of 19 electrode sites ($p < .05$). This is an interesting finding. Difference waveforms are used in an attempt to understand differences in timing of information processing, and for localisation of differences in brain function, between conditions in cognitive psychology experiments. Bates et al. did not publish sample or grand average ERPs for their two conditions nor did they publish the ERP difference waveform. However, given the finding here on the nonspecificity of the string measure, it is impossible to judge what the string measure is picking up in the difference waveform. It is also impossible to draw any reasonable conclusion on the meaning of the correlation with IQ reported in this paper.

Stough et al. (1995) investigated the effect of smoking cigarettes on the string measure. It was claimed that nicotine in cigarettes enhances information processing performance. It was also claimed that the string measure is a reliable correlate of IQ. The prediction was therefore made that smoking cigarettes would increase the magnitude of the string measure. A sample of 20 subjects participated in an ERP recording, using stimuli similar to those used by Stough et al. (1990, see Chapter 2). Two conditions were employed, a smoking and a non-smoking condition. The order of these conditions was balanced across subjects. Three repeated measures ANOVAs were used to the test the prediction that smoking cigarettes increases the string measure. Two of these were statistically significant. There are problems with this study, however, in light of the findings reported in this chapter[19]. Firstly, Stough et al. (1995) applied a band pass filter 8-35 Hz to their EEG data. This means that the frequencies that contribute most to ERP amplitude and to the string measure are missing from their ERP waveforms. Secondly, the three ANOVAs were based on waveforms that were averaged across sets of electrode sites—specifically, eight electrodes each over the left and right sides of the head running from the occiput to the frontal sites, and three midline electrodes. No justification for this procedure was made. On the basis that the brain response to tone pips is likely to be confined to auditory cortex, this averaging of the response at different sites over the scalp will produce a waveform reflecting the volume conduction of that activity to those sites. That is, it will show phase shifts and changes in amplitude and

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[19] There are several other problems with this study that are unrelated to the choice of ERP parameters. For example, blood levels of nicotine were not measured and therefore inferences on relationships between the effects of smoking and the ERP measures are suspect. Additionally, a condition that incorporated a stimulant that exerted its effect via non-cholinergic systems would be required before valid inferences on the likely causal pathways of neurotransmitter activity on information processing could be made.

likely will ‘smear’ the waveform. It is unclear what the string measure is picking up from these waveforms.

Bates et al. (1995) and Stough et al. (1995) made strong claims based on their results. Both studies appear to be flawed by their reliance on the string measure and their manipulations of the measure without regard to the physiology underlying the waveforms that the measure is applied to. Theorising based on the outcomes of these experiments is premature.

On the basis of the results reported here, it is concluded that the string measure of the ERP cannot further the understanding of the relationship between IT and IQ.

The next chapter examines the relationship between IT and IQ. Consideration is given to hierarchical models for intelligence and it is argued that this conceptualisation of human cognitive abilities may be useful for understanding the relationships which are the focus of this thesis. Finally, a series of studies that have recorded ERPs to IT stimuli is described. The material discussed in Chapter 5 forms the basis for an attempt to generate a new perspective on the processes underlying IT and cognitive abilities.

Chapter Five: Discussion on IT and IQ, Gf–Gc theory, and ERP correlates of IT

5.1 Preamble

This chapter will discuss several issues. First, the relationship of IT with IQ will be examined in detail. It will be argued that the common understanding that the relationship of IT with PIQ (from the Wechsler scales) reflects the relationship of IT with fluid abilities is questionable. Second, Gf–Gc theory of cognitive abilities will be described and an operationalisation of that theory, the Woodcock-Johnson Psycho-Educational Battery-Revised will be discussed. It will be argued that using such an operationalisation of cognitive abilities may lead to new insights on the relationship of IT with IQ. Third, research on ERPs and IT will be reviewed and the interpretations of the reported relationships between ERP measures and IT will be discussed.

5.2 IT and IQ

The theory from which the string measure arose proposed that the probability of neural transmission errors determines biological intelligence (Eysenck, 1994). It seems reasonable to equate the term 'biological intelligence' with the notion of general intelligence and Spearman's *g*. Other possibilities for the physiological factor that may determine *g* have been proposed. These include: nerve conduction velocity (NCV; Reed, 1984, 1988); quality of axonal myelination (Miller, 1994); and neural efficiency (Vernon, 1993; Haier, 1993). The validity of any measure of biological intelligence is tested by calculating its correlation with IQ, the expectation being that the correlation of a valid physiological measure of biological intelligence with IQ will be greater than the intercorrelations of IQ scores (Eysenck & Barrett, 1985, p.40). It seems to be the case then that the string measure was interpreted as a direct measure of *g* because of the high correlation of the string measure with WAIS IQ. Further support for this position derives from Jensen's (e.g., 1980, p.223) argument that the first principal component extracted from standard IQ batteries is equivalent to *g*. A similar interpretation was placed on the relationship of IT with IQ (e.g., Brand, 1984; Brand & Deary, 1982). The reasoning behind this latter interpretation and the evidence supporting this position are discussed next.

The theory that IT is related to *g* arises from Brand's (Brand, 1984, 1996; Brand & Deary, 1982) proposal that general intelligence ontogenetically depends on the speed of the brain in reacting to sensory information. IT is taken, in this theory, to be a direct measure of the speed of encoding of sensory information; and hence, individual differences in IT reflect differences in *g*. There have been two reviews[20] of the relationship between IT and IQ (Kranzler & Jensen, 1989; Nettelbeck, 1987) and two recent overviews of the measure (Deary, 1996; Deary & Stough, 1996). The two reviews covered a similar period of time and followed Lubin and Fernandez (1986) by focussing in turn on the relationships of IT with verbal, performance, and general IQ. The two reviews reached similar conclusions about the correlation between IT and IQ.

Nettelbeck (1987, p.310) provided an estimate of the correlation between IT and verbal ability of –.29; Kranzler and Jensen's (1989, p.336) meta-analysis returned an estimate of this correlation (corrected for sampling error and attenuation of range) of –.27. This finding of correlation between IT and verbal ability was taken by Kranzler and Jensen to reflect the fact that tests of verbal ability load strongly on *g*. However, they noted (p.338) that a corrected correlation of –.4 between IT and verbal ability, obtained after excluding several methodologically deficient studies from their analysis, was surprisingly low considering the extent to which tests of verbal ability load on *g*.

Performance IQ (PIQ) is a construct that derives from the Wechsler scales and is based on five non-verbal tests. Nettelbeck (1987, p.313) provided an estimate of the

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[20] An earlier review (Lubin & Fernandez, 1986) was superseded by the appearance of these two more comprehensive reviews.

correlation between IT and PIQ of –.33; Kranzler and Jensen's (1989, p.336) meta-analysis returned an estimate of the corrected correlation between IT and PIQ of –.69.

Nettelbeck (1987, p.336) estimated the correlation of IT with general intelligence (as assessed by one or more of: Wechsler full scale IQ (FSIQ); Raven's matrices; Cattell Culture Fair Test; or Stanford-Binet scales) as –.5. Kranzler and Jensen's (1989, p.336) corrected correlation was –.54. Kranzler and Jensen (p.338) concluded that "the relationship between IT and IQ seems strongest for the measures of performance IQ and weakest for the measures of verbal IQ, with the measures of general IQ in between." They therefore considered that both IT and PIQ index some abilities over and above *g*, identifying perceptual organisation as possibly being one of those abilities.

This pattern of relationships between IT and IQ has been demonstrated in many studies over the years since the reviews by Nettelbeck (1987) and Kranzler and Jensen (1989) were published (see Deary 1996; Deary & Stough, 1996). An examination of the abstracts of 17 recent studies[21] on the relationship of IT with intelligence (Alcorn & Morris, 1996; Bates & Eysenck, 1993; Bowling & Mackenzie, 1996; Caryl & Harper, 1996; Caryl, Golding & Hall, 1995; Deary, 1993; Deary, Caryl, Egan & Wight, 1989; Egan, 1994; Evans & Nettelbeck, 1993; Ferrando, Vigil, Lorenzo & Tous, 1993; Holahan & Smith, 1992; Kirby & Nettelbeck, 1991; Knibb, 1992; Morris & Alcorn, 1995; Stough, Brebner, Nettelbeck, Cooper & Bates, 1996; Zhang, 1991; Zhang et al., 1989b) revealed that all had used tests of general intelligence (most commonly, Raven's matrices or WAIS IQ). However, two studies (Cooper, Kline & MacLaurin-Jones, 1986; Nettelbeck et al., 1986) have tested the relationship of IT with primary ability measures. One aim of these studies was to define which second-order abilities (as described by, for example, Horn, 1988; Horn & Noll, 1994; Kline, 1991;

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[21] These studies were selected on the basis that the type of cognitive test used was directly discernible from the abstract of the article.

Carroll, 1993) are associated with IT. Before describing these studies a brief digression into theories of human abilities is necessary.

5.2 The Horn-Cattell Gf–Gc theory of intelligence

The psychometric view of intelligence depends on factor analysis (Kline, 1991). Models of intelligence derived from factor analysis describe the relationships of various abilities that form the structure of intelligence (Carroll, 1993, p.52). Those models of intelligence that are based on factor analysis can be classified into two broad categories (Stankov & Roberts, 1997). The first category is of models which propose that a single general factor explains substantial variation in intelligence. Models that exemplify this position derive from Spearman (1927). Spearman's model hypothesised that there is one factor common to all cognitive abilities, despite specificity defining each such ability; this factor was described by Spearman (pp.161-198) as the ability to educe relations and correlates. The second category is of models that propose several 'general' or broad factors (e.g., Thurstone, 1938; Vernon, 1961; Horn & Cattell, 1966). Carroll (1993, pp.624-625), on the basis of his reanalyses of a large database of factor analytic studies, concluded that Horn and Cattell's model, known as Gf–Gc theory (for general fluid and general crystallised ability) was largely supported. However, Carroll also found evidence for a higher order factor of general ability due to the intercorrelation of the factors described in Gf–Gc theory (which are second-order abilities). This general factor is therefore not identical with Spearman's *g* which has commonly been identified with the second-order factor of fluid ability (i.e., Gf)[22]. Or, to

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[22] This distinction is influenced by (and influences) the particular factor analytic technique used. That is, in the case of some hierarchical models (e.g., Vernon, 1961) a general factor (first principal component or factor) is extracted and the remaining variance is then accounted for by subsequent factors. This type of analysis requires that a general factor account for as much of the variance as possible. The second approach sees a general factor emerge at a higher order as the result of the correlations between the primary or second-order factors.

put it another way "Gf may be a good indicator of Spearman's concept of *g*, but it is not a good indicator of the entire repertoire of human intellectual abilities" (Horn, 1988, p.654).

Horn (1985, 1987, 1988; Horn & Noll, 1994) has described Gf–Gc theory and a summary of this model is now given. Essentially, the model postulates a hierarchy of abilities. At the first (lowest) level of the hierarchy are what may be termed primary cognitive abilities. Examples of these primary abilities include: verbal comprehension; number facility; concept formation; temporal tracking; and perceptual speed. Horn (1985, 1988) made the point that the number of these abilities is probably unknowable and is also not fixed. By this he meant that humans have the facility to develop new capabilities in response to, for example, new technologies. Carroll's (1993, Figure 15.1, p.626) analyses showed 70 first-order factors reliably identified on the basis of the tests that load on them.

Factor analyses have identified about nine broad second-order abilities based on the relationships of the first-order factors to each other. The nomenclature used by Horn and others (Horn, 1994; Stankov & Roberts, 1997) is followed here but the same factors are described using somewhat different terminology by Carroll (1993). Table 5.1 outlines these broad abilities and describes typical primary abilities that define each of them.

A key feature of this model of cognitive abilities is that each of the second-order abilities describes some aspect of what is generally taken to be intelligence. As Horn puts it, Gf–Gc theory is a theory of multiple intelligences (Horn & Noll, 1994, p.198). Apart from evidence based on factor analytic studies, Gf–Gc theory is supported by developmental studies. That is, the different second-order abilities show different patterns of change across the life-span. Thus, Gf and Gs both reach a peak in early adulthood and then decline with advancing age. On the other hand, Gc increases beyond childhood into adulthood and is maintained into the sixth or seventh decade of life. Because of this dissociation across time, the conclusion is drawn that these abilities are largely independent. Stankov and Roberts (1997, p.74) argue that each of the broad abilities are important and that none is subordinate to any of the others. However, they also point out that because these factors share common variance then the processes underlying each are to some extent related. That is, Gs (or Gv) has some role in Gf, and so on.

The strength of the evidence supporting Gf–Gc theory and Carroll's (1993) three-stratum theory (these are largely consistent with each other) suggests that investigations of the relationship between IT and IQ be broadened. That is, heretofore the research programs of most investigators in the field have used measures of general intelligence. As the reviews by Nettelbeck (1987) and Kranzler and Jensen (1989) showed, IT is related differentially to measures of verbal, performance and general IQ. These patterns of relationships have been interpreted by some within a framework that proposed that, for example, speed of processing determined general intelligence. This interpretation is challenged by Gf–Gc theory because speed of processing (Gs) is shown to be not a single, fundamental entity (Roberts & Stankov, 1994; Stankov & Roberts, 1997). Two studies that have sought to locate IT within a broader framework of cognitive abilities are now discussed. Additionally, Deary's (1993) factor analytic study of the relationship of IT with WAIS-R subtests is discussed.

5.3 IT and broad cognitive abilities

The first two studies to be reviewed here (Cooper et al., 1986; Nettelbeck et al., 1986) sought to broaden the understanding of the relationship of IT with general ability by conducting studies that included various tests of first-order (primary) abilities. Both studies included tests from Cattell's Comprehensive Ability Battery (CAB); Nettelbeck et al. also included the APM in their battery of tests.

Table 5.1

Broad abilities described in Gf–Gc theory and examples of the primary abilities that define them.

Factor and symbol	Description of ability	Example of primary ability or test and comment
Fluid intelligence (Gf)	Perceiving relationships; drawing inferences	Matrices. Concept formation. Inductive reasoning.
Crystallised intelligence (Gc)	Knowledge; scholarship; experience; culturally valued learning; acculturation	Verbal knowledge. Vocabulary. Comprehension. Information.
Short-term acquisition and retrieval (SAR or Gsm)	Immediate apprehension; working memory	Memory span. Digit span.
Retrieval from long-term storage (TSR or Glr)	Fluency and breadth of use of stored material (time scale of minutes to years)	Retention of learning. Ideational fluency.
Visual processing (Gv)	Visual closure and constancy; fluency of spatial perception	Gestalt closure. Visual manipulation. Visual constancy.
Auditory processing (Ga)	Perception or discrimination of auditory patterns, especially under distraction or distortion	Maintaining and judging rhythms. Sound blending.
Processing speed (Gs)	Rapid scanning and responding in simple tasks	Digit symbol. Clerical speed.
Correct decision speed (CDS)	Quickness in providing answers	No standard test. Low correlation with Gs.
Quantitative knowledge (Gq)	Application of mathematical skills	Distinguished from Gf by requirement for application of principles of mathematics.

Note. Based on Horn (1987, 1988; Horn & Noll, 1994), Carroll (1993), Stankov & Roberts (1997)

Cooper et al. (1986) described the aim of their study as being to determine whether IT reflects differences in Gf and/or Gc, or whether other second-order factors are more important in determining IT. There were 20 subjects (age range 19 to 40 years) of whom 18 were undergraduate students. Seventeen tests from the CAB were completed, along with IT estimation.[23] Of 17 correlations between IT and the abilities tests, six were significant (four at $p < .05$ and two at $p < .01$, all tests one-tailed). The tests that correlated significantly with IT were associated with the second-order factors of visualisation (i.e., Gv) and speed (i.e., Gs) but not with Gf or Gc.

Nettelbeck et al. (1986) reported the results of two experiments relevant to the question of mental speed and cognitive ability. The first experiment was similar to that reported by Cooper et al. (1986). There were 30 subjects (age range 20 to 40 years) of whom 12 were university graduates. Nine tests from the CAB (all of which were also included in Cooper et al.'s battery), the Digit Span (forwards and backwards, from the WAIS-R) and the APM were completed, along with IT estimation.[24] Of 12 correlations between IT and abilities tests, three were significant ($p < .05$, one-tailed). These correlations were with APM, associative memory, and Digit Span (forwards). This result is difficult to interpret in terms of second-order abilities and the authors noted that the outcome was more consistent with a general ability model.[25] However, in contrast with Cooper et al., IT was not associated with

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[23] Cooper et al. (1986) used a version of IT known as the '2-lights task'. In this version of IT, a subject is required to discriminate which of two adjacent lights is illuminated first. The two target lights are part of a larger array of lights (i.e., there may be a line of four or six lights and the target lights are the central pair). This version of the task has not been as widely used as the two lines version although recent evidence (Burns, Nettelbeck and White, 1998) suggests that that these tasks are probably equivalent.

[24] In this experiment, '2-lines IT' and an auditory IT task were completed. Auditory IT has not proven to be a reliable correlate of visual IT (Nettelbeck, 1987). For that reason and because this thesis mainly focusses on the visual system, the results of Nettelbeck et al. (1986) on auditory IT are not considered here.

[25] The correlation of IT with APM supports this interpretation because this test is widely considered to be a good measure of general ability. However, according to Carroll (1993, p.696) progressive matrices tests load on the second-order factor he terms 2F (i.e., fluid ability or Gf in the terminology adopted here). He also noted that there is some evidence that progressive matrices have a component that requires spatial abilities (Gv). This leads to the possibility that in samples which are homogeneous in general (or fluid) ability the matrices differentiate subjects on the basis of the Gv requirement (see also Kline, 1991, p.56). Carroll also recommended

any tests that clearly loaded on Gv or Gs. The second study reported by Nettelbeck et al. was concerned with the second-order ability of correct decision speed (CDS).[26] There were 43 subjects (age range 17 to 40 years) of whom 33 were undergraduates. The WAIS-R was completed. Additionally, the six items from the E-series of the PM were completed. The time taken to reach the solution to these items was recorded and was interpreted as a measure of CDS. Correlations of IT with WAIS-R IQ were consistent with the discussion above—i.e., significant correlations ($p < .01$, one-tailed) in the order PIQ > FSIQ > VIQ. The mean correlation of IT with the measures of CDS (time taken to reach the solution) was .31. Nettelbeck et al. noted that the correlations of IT with the subtests constituting the PIQ scale suggested that "IT-IQ covariation could be limited predominantly to a general perceptual–spatial capacity."

Overall, the studies of Cooper et al. (1986) and Nettelbeck et al. (1986) provided some evidence that IT may be related to second-order abilities of Gv, Gs and CDS rather than to Gf or Gc. However, these findings need to be placed in a wider context. To explain: support for this interpretation requires some resolution of the finding that IT correlates more highly with PIQ than with VIQ or general ability. That is, the ability (or abilities) measured by the PIQ scale must be identified. Deary's (1993) factor analytic study of IT and the WAIS-R provides useful data towards such a resolution and is discussed next.

In his introduction Deary (1993) discussed the widely held assumption that the VIQ scale of the WAIS-R is an indicator of Gc and that the PIQ scale is an indicator of Gf. He noted that this assumption arises in part because of the developmental profile of the two

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that there be control for speed in the administration of the progressive matrices test. This last point emphasises that when the matrices are administered under timed conditions the second-order factor Gs may also be measured.

[26] It should be noted that Nettelbeck et al. (1986) did not use this terminology. However, the description of their rationale is entirely consistent with Horn's (1988) description of this second-order ability.

scales, and in part from a content analysis of the two scales. Thus, it was noted that generally PIQ declines with age whereas VIQ does not. As discussed above, this is the pattern that holds for Gf and Gc, respectively. However, because decline with age is also seen for Gv and Gs, then evidence that PIQ declines with age is, of itself, not unequivocal support for the proposition that PIQ is an indicator for Gf. The proposition that VIQ is closely related to Gc is reasonable on the basis of a content analysis of the verbal subtests (Kline, 1991, pp.50-51). The performance subtests on the other hand are not unambiguously interpretable as being related to Gf.

Deary's (1993) study was designed to test whether IT has significantly different correlations with PIQ and VIQ. There were 87 subjects (age range 27 to 52 years; mean age 40.5, $SD = 6.2$ years) all of whom were insulin-treated diabetics. Nine of the 11 subtests of the WAIS-R were completed (Digit Span and Picture Arrangement were excluded because of time constraints). Correlations of IT with WAIS-R IQ score were again consistent with the pattern described above. The correlations were –.35 ($p < .001$), –.25 ($p < .05$) and –.14 (ns) with PIQ, FSIQ and VIQ, respectively. Factor analysis described a solution with two orthogonal factors identified, on the basis of the loadings of the subtests, as verbal and performance factors. IT had near-zero loading on the verbal factor and a loading of –.67 on the performance factor. This analysis confirmed the pattern identified by Nettelbeck (1987) and Kranzler and Jensen (1989). Deary summarised his findings by suggesting that the results were consistent with the proposition that IT may be related to Gf. Evidence from developmental studies of IT provided further support for the suggested relationship. Deary indicated that a direct test of this hypothesis was required.

In summary, the finding that IT loads on PIQ does not provide unequivocal support that IT is related to Gf. This is because the WAIS-R was not designed to test such a model of cognitive abilities. Rather, it was designed on the basis of the intuitions and experience of its constructor and the tests included were meant to "provide an effective adult scale" (Wechsler, 1939, cited in Frank, 1983, p.9). Two questions arise from the above considerations: first, what are the latest findings about the WAIS-R scales in terms of Gf–Gc theory?; and second, what would be an adequate test of the hypothesis that IT is associated with Gf? These questions are addressed in the next two sections of this chapter.

5.4 PIQ and second-order abilities

Carroll (1993, p.702) considered the WAIS-R in the context of his three stratum theory of cognitive abilities. He stated that factor analytic studies of the WAIS-R "almost invariably show three factors, a verbal or language development factor found principally in some of the verbal subtests, a spatial or visualization factor found principally in some of the performance subtests, and a further factor in the memory span[27] and digit symbol subtests that is probably a combination of factor MS (memory span) and P (perceptual speed) ... the Verbal scale can be taken as an approximate measure of the second-stratum factor Gc, while the Performance scale can be taken as an approximate measure of factor Gv, or somewhat less validly of factor Gf." On the basis of this analysis of the WAIS-R, the correlation of IT with PIQ is still ambiguous in terms of whether IT is related to Gf rather than to Gv or Gs, or both.

Woodcock (1990) provided strong evidence that the Wechsler scales do not measure Gf. The evidence provided is based on data from the standardisation sample from the Woodcock-Johnson Psycho-Educational Battery-Revised (WJ-R; Woodcock & Johnson, 1989) and the WJ-R concurrent validity samples (McGrew, Werder & Woodcock, 1990), supplemented with data from the standardisation sample and concurrent validity samples from the Woodcock-Johnson Psycho-Educational Battery (WJ; Woodcock & Johnson, 1977). The WJ-R Tests of Cognitive Ability are an operationalisation of Gf–Gc theory and provide

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[27] The absence of the Digit Span test from Deary's (1993) battery may account for only two factors being defined in his analysis.

measures of seven of the second-order abilities described in Table 5.1 (above).[28] The battery as a whole provides measures for eight of the second-order abilities; only CDS is not measured by the WJ-R. Woodcock (1990, p.240-241) demonstrated via confirmatory and exploratory factor analyses on the standardisation sample ($N = 2261$) that the WJ-R provides two tests for each of seven Gf–Gc factors.

Woodcock's (1990, p.242-243) Table 5 consolidated data from 15 confirmatory factor analytic solutions on 9 data sets. The information relevant to this discussion concerns PIQ subtests from the Wechsler scales and their loadings on the second-order abilities defined by Gf–Gc theory. These data are presented in Table 5.2.

The data in Table 5.2 show that the five subtests which constitute PIQ have their highest loadings on Gv and Gs. Two of the subtests also have minor loadings on Gc and one subtest has a minor loading on Gf. The PIQ score, which is a weighted average of the standardised scores on the five subtests, must represent a mixture of Gv and Gs but is not a clear measure of either. This means that the correlation between IT and PIQ most likely depends on IT sharing variance with visualisation ability or processing speed or both. It is unlikely that the correlation of IT with PIQ depends on shared variance with Gf or, by extension, with *g*.

An adequate test of the hypothesis that IT is associated with the second-order ability Gf, as has been widely assumed, could be achieved by administering tests that are markers for second-order abilities to a representative sample of subjects. The WJ-R provides tests that are good markers for seven second-order abilities. A copy of this test was therefore purchased and evaluated. The outcome of this evaluation (see Appendix II) was that the WJ-R would be used in the investigation of the relationship of IT with cognitive abilities.

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[28] The WJ-R tests of cognitive ability are discussed more fully in Appendix II.

Table 5.2

Median factor loadings of Wechsler PIQ subtests on factors defined by 15 analyses of 9 data sets from the WJ-R and WJ standardisation and concurrent validity samples[a]

	Factor						
PIQ subtest	Glr	Gsm	Gs	Ga	Gv	Gc	Gf
Picture Completion	–	–	–	–	.453	.248	–
Picture Arrangement	–	–	–	–	.197	.315	–
Block Design	–	–	–	–	.578	–	.123
Object Assembly	–	–	–	–	.622	–	–
Digit Symbol	–	–	.582	–	–	–	–

Note. The symbol (–) indicates that the fitted models in more than half of the analyses had these loadings fixed at zero.

[a]Source: Adapted from Woodcock (1990, p.242-243).

As discussed in the preamble to this chapter, the issue of which aspects of cognitive abilities are related to measures derived from the ERP must also be addressed. Little work has been published that has related ERP measures to measures of broad cognitive abilities. As was the case with studies on IT and IQ, most researchers have used measures of general ability. For example, the string measure of the ERP was taken to be a direct measure of *g*. Given the focus of this thesis on the relationship between IT and cognitive abilities, a review of all the literature on ERPs and measures of IQ would be too broad. Rather, this review will be restricted to those studies that have recorded ERPs during the measurement of IT and to studies that have related ERP measures (other than the string measure) to IT. A feature of all these studies has been that the ERP measures were tested for correlations with both IT and IQ.

The point of this, as discussed below, was to clarify what it is about IT that leads to its relationship with IQ.

5.5 ERP correlates of IT and IQ

There are seven papers that have reported correlations between ERPs and IT; six of these studies have also reported correlations between ERPs and IQ. Six of the seven studies reported measures from ERPs that were recorded as subjects were engaged in an IT task and one study reported correlations of IT with ERPs recorded during an auditory oddball task. An eighth paper has discussed the effects of task difficulty and threshold on ERPs recorded during an IT task. These studies are now discussed.

The first two of these studies (Zhang et al., 1989a, 1989b) reported some findings from Zhang's (1987) investigations that formed part of his doctoral dissertation. Zhang et al. (1989a, p.379) argued that ERPs produced by the visual stimuli of the IT task would provide evidence as to "the stage or stages of information processing IT may reflect." Their rationale (p.380) was as follows: (1) positive correlations between P200 "temporal measures" and IT would indicate that "IT indexes the processes of encoding as a prelude to the subsequent process of information evaluation or analysis"; (2) "a positive correlation of the P300 latency with [IT] implies that, because the measure of the P300 latency includes that of the P200 latency, [IT] may reflect the overall speed of those processes in which sensory information is encoded and evaluated"; and (3) positive correlation between IT and the difference between the latencies of P300 and P200 (i.e., peak-to-peak latency) would indicate that IT indexes "the speed of the process which evaluates the encoded information."[29]

There were 16 subjects (mean age 28.1, *SD* = 7.99 years). EEG was recorded from Cz referred to the left mastoid. Sampling rate was 1000 Hz and recording began at the onset

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[29] This rationale will be discussed further in the summary of these eight studies, below.

of the IT cue and continued for 1024 ms. The EEG was recorded as IT was estimated (by an adaptive staircase procedure), and SOA was fixed at the subject's IT estimate as soon as this estimate was obtained. There were always 100 presentations of the IT stimulus. ERPs were constructed to the onset of the IT target figure. Measures taken from the ERPs were latencies of P200 and P300, the difference between these latencies, and a rise time measure of the P200. This latter measure arose from an observation by Zhang (1987, p.58) that subjects (in a pilot study) with short IT estimates had "steeper slopes in the N150-P200 complex." The P200 rise time measure was defined as the time from the intersection of the ERP trace with a baseline (defined in this experiment as the mean potential for the epoch 75 - 275 ms from stimulus onset) to the point of maximum amplitude of the P200. The only significant correlation found was .44 ($p < .05$, one-tailed) between IT and the P200 rise time measure. Zhang et al. interpreted their finding as supporting the view that IT measures the speed of encoding from a sensory register into short-term memory. They also argued that their finding provided support for the proposition that speed of information processing is an underlying requirement for high intellectual ability (p.383).

Zhang et al. (1989b) described three experiments. The first two were small scale studies that provided important data on the effect of manipulating SOA (and hence task difficulty) in the IT task on ERPs recorded as the task was performed. These two experiments used three separate types of IT trials. In both experiments one of these condition consisted of trials set at the IT estimate of the subject (IT was estimated at the 90% level of accuracy). The other two conditions were of trials in which it was either very difficult or very easy to make the required discrimination. In the first experiment this manipulation was achieved by presenting trials that were either 0.25 times the IT estimate or 1.75 times the IT estimate. In the second experiment the easy trials were unmasked presentations of the IT target figure and the difficult trials were presentations of the mask only (i.e., SOA = 0 ms). There were eight subjects in each experiment (Experiment 1, mean age 24.1, *SD* = 2.94 years; Experiment 2, mean age 23.0, *SD* = 2.64 years). EEG recording details were as described for Zhang et al. (1989a). Results of these experiments demonstrated that P300 amplitude was sensitive to SOA [$F(2, 14) = 5.47, p < .05$ for Experiment 1; and $F(2, 14) = 4.37, p < .05$ for Experiment 2] and greatest in the 'easy' trial conditions. There was no effect on P300 latency. Similarly, there was no effect of SOA on P200 latency, amplitude, or rise time. Zhang et al. (1989b) combined the ERP data from both experiments (i.e., $N = 16$) and calculated correlations between the ERP measures and IT. As with Zhang et al. (1989a), the only significant correlation found was .58 ($p < .05$) between IT and the P200 rise time measure. Taken together, these results demonstrated that the correlation between IT and P200 rise time was not dependent on the SOA of the IT trials presented during EEG recording because the rise time measure did not vary with manipulation of SOA.

The third experiment reported by Zhang et al. (1989b) was cleverly designed to extend the findings thus far reported by testing correlations of the ERP measures with IQ. The effect on ERP waveform of a requirement to make a discrimination, or not, involving the IT target was also examined. Thus, each trial was preceded by a 300 ms cue. This was followed, after 200 ms, by the presentation, for 512 ms, of either one of two alternative numeric digits (made up of LED elements). One of these digits signalled that the following IT trial was to be responded to in the usual way and the other signalled that the IT trial was to be ignored. There were equal numbers of both types of trials. After 200 ms, the IT target figure was presented, followed after a fixed SOA by the mask. A response signal was lit, 500 ms after mask offset. For the trials in which IT was to be discriminated, this signal prompted the subject to indicate, responding as quickly as possible by pressing the corresponding lever, which leg of the IT figure was longer. In the trials for which no discrimination was required, the subject responded by pressing a previously designated lever as quickly as possible. There were 40 subjects (mean age 19.6, range 18 to 21 years), and 38 of these subjects completed the Alice Heim 5 (AH5) test of IQ. EEG recording details were as described for the previous experiments but with the addition of a second EEG electrode at Oz. Two ERPs were constructed, one to the signalling digit and one to the IT target figure[30]. These ERPs were 550 ms in duration, beginning 50 ms prior to the stimulus onset.

The ERPs to the unmasked signalling digit were not significantly different at either electrode site until latency reached about 300 ms. The P300 amplitude was greater for the unmasked digit that signalled that the IT trial was to be discriminated than for the digit that signalled that the IT trial was not to be discriminated. This finding was repeated at Oz for the ERPs for the IT target figure. At Cz the P200 amplitude was greater in the trials where discrimination was required than in the trials where no discrimination was required. Correlations of the ERP measures from Cz (these were not reported for Oz) with IT were as follows: for the signalling digits, .00 (ns) and .29 ($p < .05$, one-tailed) with P200 latency and rise time, respectively; for the IT trials where no discrimination was required, correlations were not significant; for the IT trials where discrimination was required, .44 and .65 ($p < .01$) with P200 latency and rise time, respectively. Correlations with P300 measures were not significant. These results were therefore consistent with those described above—that is, the P200 rise time measure correlated most highly with IT. The P200 rise time measure from the digit stimulus ERP correlated with AH5 IQ –.34 ($p < .05$). No other correlations with AH5 were significant.

Colet, Piera and Pueyo (1993) showed that the correlation between IT and P200 rise time generalised to ERPs recorded to auditory stimuli. Subjects were 240 undergraduates (mean age 21.7, *SD* = 3.2 years). EEG was recorded from Cz and Fz referred to A1 and A2,

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[30] Zhang et al (1989b) did not specify the SOA of the IT trials but reference to Zhang (1987, p146) confirmed that the trials were set at the previously estimated (at the 85% level of accuracy) IT of the subject.

respectively. The recording epoch was 500 ms and frequency passband was 1 to 30 Hz. Stimuli were tones at two frequencies (800 Hz and 1500 Hz), presented in random order. The subject's task was to count the higher tones which had a probability of occurrence of .2. EEG recording continued until 60 presentations of the rare tone had occurred; the ERPs were constructed for the rare tones only. ERP data for 40 subjects were rejected because of artefacts. Correlations of IT with P200 rise time were .41 and .56 and with P300 latency were .40 and .36, for Cz and Fz, respectively (all $p < .01$). No other correlations were significant.

Caryl (1994) introduced two manipulations on the IT task and examined the effects of these manipulations on task performance and on the ERP waveform. The first manipulation was of the interval between the offset of a warning cue and the onset of the IT target figure (i.e., cue-stimulus interval; CSI). Three CSIs were used: 1850 ms, 1100 ms, and 500 ms. The second manipulation was of the SOA, which was varied systematically from 50 ms to 10 ms in 5 ms steps. Caryl also reported correlations of IT and AH5 IQ with N140, P200 and P300 latencies and amplitudes. Also presented were what Caryl referred to as "continuous amplitude and gradient measures of ERP waveform" (p.30). These latter measures were used to plot the change, over the ERP epoch, of the correlations between these measures and IT and IQ. To explain, these measures were: first, amplitude of the ERP at a given time point; second, the gradient of the ERP at a given time point. The latter measure was defined as the gradient of a straight regression line over a 32 ms window centred on the time point. The correlation (with IT and IQ) of each measure at each time point was calculated and plotted against time. The point of this was to examine at which latencies the greatest correlations with IT and IQ were found.

Subjects were 35 undergraduates (mean age 19, range 17 to 28 years), 28 of whom completed the AH5. EEG was recorded from Cz referred to the left mastoid, the sampling rate being 1000 Hz. There were 270 trials, presented in blocks of 30 trials. Each CSI was presented 10 times in each block and order of presentation was randomised. SOA was constant within a block, and was decreased by 5 ms for each successive block. ERPs were constructed to the cue (350 ms epoch beginning 50 ms prior to cue onset) and to the IT target figure (650 ms epoch beginning 50 ms prior to IT target figure onset). Caryl (1994, p.29) reported the median correlations (across three CSIs) of ERP peak latencies and amplitudes with IT and IQ. The significance levels of correlations were not reported but the correlations of P200 latency with IT, for both the cue ERP and the IT figure ERP, would be significant (both $r = .31, p < .05$, one-tailed). No other correlations were significant.

The continuous amplitude and gradient measures are now considered. The gradient measure correlated with IT at latencies of about 150 ms post stimulus for both the cue and IT figure ERPs; the maximum correlation was –.55. Significance of these correlations cannot be satisfactorily assessed because successive time points are highly correlated. However, by using bootstrap estimates, Caryl (1994, pp.32-33) determined that these maximal correlations were unlikely to have arisen by chance. The gradient measure from both ERPs also correlated with IQ at about the same latencies; the maximum correlation was .60. Moderately high correlations, in the opposite directions than found at 150 ms, were also found at latencies of about 110 ms (i.e., .40 for IT and –.64 for IQ). Correlations of the continuous amplitude measure with IT and IQ were similar to those reported for the gradient measure. All these correlations were consistent with the earlier findings on P200 rise time because a 'steeper' gradient measure would imply a shorter rise time measure.

Caryl, Golding and Hall (1995) reported data that were concerned with ERP studies on auditory IT and pitch discrimination. Additionally, they presented an elaboration of the bootstrap technique for estimating confidence limits on the continuous amplitude and gradient measures described by Caryl (1994). The IT data from Caryl (1994) were reanalysed in this paper and evidence was therefore provided from a somewhat different statistical procedure confirming the findings presented in the earlier paper. "Certain critical parts of the epoch ... the rising phase of the P200 and also in the region of N100" differentiated subgroups of the sample that were low or high on either IT or IQ. (Caryl et al., p.312)

Morris and Alcorn (1995) reported an experiment that differed somewhat from those discussed so far. ERPs were recorded in a task that was referred to as IT. The task required the subject to report which of four possible, backwardly masked letters had been presented. Subjects were 49 undergraduates (ages not specified), all of whom completed Raven's PM. It is not clear how many EEG channels were recorded but the paper reported results for four channels only: O1, T5, T3 and F7. Two EOG channels were also recorded and sampling rate for all channels was 100 Hz. IT trials were presented at six SOAs (17, 34, 50, 67, 84 and 100 ms). Trials were presented in either increasing or decreasing order of SOA, with two trials at each SOA before moving to the next higher (or lower) SOA. The four target letters were presented 60 times each, with order randomised across trials. The dependent variable was not an estimate of IT but was the recognition accuracy (RA) at each SOA. The correlations of this RA measure with PM were .44 and .38 ($p < .01$) at the two shortest SOAs, respectively; correlations at the longer SOAs were not significant. Because RA at any given SOA would depend on IT this finding is consistent with the usual correlations of IT with IQ.

The ERP measure that Morris and Alcorn (1995) calculated was the slope of the P200 deflection. This measure (μV/ms) was defined as the ratio of peak-to-peak amplitude to peak-to-peak latency of the N150-P200. Correlations of the P200 slope measure with RA (at the two shortest SOAs) and PM and were reported from ERPs recorded at each SOA. The median correlations (over SOAs) between P200 slope and RA (SOA = 17 ms) were .34 ($p <$ .05), –.02 (ns), .30 ($p < .05$) and 20 (ns) for F7, T3, T5, and O1. respectively. The median correlations (over SOAs) between P200 slope and PM were .47 ($p < .001$), –.16 (ns), .33 ($p <$

.05) and –.05 (ns) for F7, T3, T5, and O1. respectively. Correlations between P200 slope and RA (for SOA = 34 ms) were not significant.

Alcorn and Morris (1996) reported data on P300 latency and amplitude from the same experiment as reported by Morris and Alcorn (1995). The median correlation (over SOAs) between P300 amplitude and PM at site O1 was .33 ($p < .05$). No other correlations were significant.

Caryl and Harper (1996) presented reanalyses of data reported by Caryl et al. (1995) and Caryl (1994). The rationale for these reanalyses was to test the proposition that task difficulty may affect the ERP waveform. That is, as Caryl and Harper (pp.2-3) explain, when ERPs are recorded during a task that is not trivially simple then there may be a confounding of task threshold (for an individual) and task difficulty. If subjects are presented with a standard range of SOAs, then difficulty of discrimination (for a given subject) across SOAs will vary depending on that subject's threshold (i.e., IT). If ERPs are constructed by averaging across SOAs, then between-subject variability in the ERP may be attributable to variance in either threshold, or difficulty, or both. Caryl and Harper argued that this may be a particular problem when ERPs are recorded during procedures that use adaptive staircase algorithms to estimate IT.[31] However, Caryl and Harper noted that previous research (as summarised above) had demonstrated: (1) ERP measures from tasks that were free of possible confounding with task difficulty were correlated with both IT and IQ (e.g., ERPs from the cue used in IT tasks [Caryl, 1994], and ERPs from unmasked stimuli [Zhang et al., 1989b]); and (2) that systematically varying task difficulty (Zhang et al., 1989b) did not affect correlations of P200 measures with IT. Nevertheless, Caryl and Harper (p.5) argued that a "systematic analysis of the role of task difficulty on ERPs in the elementary tasks, such as IT, that are now

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[31] Discussion of this latter point will be deferred until this review of the ERP–IT literature is summarised (see below).

used in the literature on intelligence" was required. Particular emphasis was placed on the latency at which the effects (if any) of task difficulty on the ERPs occurred.

For reasons given elsewhere, the results on pitch discrimination will not be considered here. For the IT data reanalysed in the paper under discussion, Caryl and Harper (1996) defined three levels of IT task difficulty by collapsing the nine SOAs used by Caryl (1994, see above) into three levels. These three levels were classified as: 'easy' (SOAs 40, 45 and 50 ms); 'medium difficulty' (SOAs 25, 30 and 35 ms); and 'hard' (SOAs 10, 15 and 20 ms). Two subgroups of subjects (*N* = 10, in each group) were also defined as being of high- or low- IT threshold. ERP measures reported were the latency and amplitude of the following deflections: N100, P200, N240 and P300. Additionally, 'window analyses' of component amplitudes were made. These were the average voltages over three windows: N100 (100 - 150 ms), P200 (175 - 225 ms) and P300 (250 - 450 ms). Repeated measures ANOVAs were performed with task difficulty and CSI (see above) as the within subjects factors. At each time point, a one-way ANOVA was calculated to provide a "continuous index of task difficulty on ERP waveform" (p.10). The effect of task difficulty was confined to the P300 deflection. This finding was consistent with previous research on this component. That is, P300 amplitude was greater when the task was 'easy', whereas P300 latency increased when the task was 'hard'. There was no effect of task difficulty on the P200 measures. Of particular note, is that Caryl and Harper (p.13-15) demonstrated that the P200 gradient measure was unaffected by task difficulty.

5.6 Summary and Discussion of ERP studies on IT and IQ

The findings reviewed above will be discussed under the following headings: (1) correlations of ERP measures with IT; (2) correlations of these ERPs with IQ; (3) effects of manipulations of the IT task on ERPs recorded during IT task performance. The implications of these findings will then be discussed. Finally, the assumptions underlying the interpretations of these studies by their authors will be examined.

5.6.1 Correlations of ERPs with IT

Under this heading, results from ERPs recorded to the IT stimuli will be considered separately from ERPs recorded to unmasked stimuli. For the former group of studies correlations of IT with P200 latency, amplitude, rise time and slope are considered first. The weighted mean of significant correlations between P200 latency and IT was .37 ($N = 69$). There was one significant correlation between P200 amplitude and IT of .33 ($N = 37$). The weighted mean of significant correlations between P200 rise time and IT was .58 ($N = 69$). The mean of significant median correlations (at SOA = 17 ms) of P200 slope with IT was .32 ($N = 37$). Correlations of IT with P300 latency and amplitude are considered next. No significant correlations with P300 latency were reported. The weighted mean of significant correlations between P300 amplitude and IT was .34 ($N = 83$). Turning to the unmasked stimuli, these ERPs were recorded either to 'cue' stimuli, or to IT targets that did not require discrimination, or to auditory oddball stimuli. The first two types of stimuli will be considered together and the latter type will be dealt with separately. For the cue and non-discriminated IT figure ERPs, there was one significant correlation of .31 ($N = 31$) between P200 latency and IT. There were no significant correlations between P200 amplitude and IT. There was one significant correlation of .29 ($N = 29$) between P200 rise time and IT. For these ERPs, P300 deflections were usually absent or poorly defined and therefore correlations with P300 were not reported. In the auditory oddball experiment of Colet et al. (1993), correlations with P200 latency were not significant (amplitude measures were not reported). The mean correlation (over two electrode sites) between P200 rise time and IT was .48 ($N = 200$). The mean correlation of P300 latency with IT was .38 ($N = 200$).

The pattern of correlations over these several studies appears to be as follows: first, for the visual stimuli (i.e., unmasked cues, IT targets not discriminated, and IT targets) there was a correlation between P200 latency and IT of about .3. This correlation did not hold for the auditory oddball P200 latency; second, for all ERPs there was a correlation between P200 rise time and IT of about .5. The robustness of this latter relationship was demonstrated by the finding that the correlation of P200 slope with IT was about .3. Further, the maximal correlations of the continuous gradient measure of Caryl (1994), at latencies of about 150 ms, are consistent with the rise time correlations; third, correlations of IT with P200 and P300 amplitude and with P300 latency were not consistent across ERP types and do not appear to be robust.

5.6.2 Correlations of ERPs with IQ

Correlations of these ERPs with IQ are now considered. There was a correlation between the P200 rise time from an ERP recorded to an unmasked signalling digit and AH5 of –.34 ($p < .05$, one tailed, $N = 35$). From the Morris and Alcorn (1995) and Alcorn and Morris (1996) reports ($N = 49$) there was a mean significant median correlation (at SOA = 17 ms) of P200 slope with PM of .40. There was a mean significant median correlation (at SOA = 17 ms) of P300 amplitude with PM of .33. The correlations of Caryl's (1994) continuous gradient measure with AH5, at latencies of about 150 ms, lend some generality to the correlations found between P200 rise time or slope with IQ. However, the relationship may not be as robust as that found between P200 rise time and IT.

5.6.3 Results from Caryl's studies

The final group of studies to be discussed is that of Caryl and co-workers (Caryl, 1994; Caryl et al., 1995; Caryl & Harper, 1996). Some of their results have been summarised already. This discussion concerns the manipulations on the IT task that were tested for their effects on ERP waveforms and the implications of the findings for the generality of correlations of ERP measures with IT and IQ. The first manipulation to be discussed was that of cue stimulus interval (CSI). It was found that only very short CSIs had any effect on ERP waveforms and this effect was confined to latencies from about 240 ms onwards. Therefore, CSI is unlikely to affect correlations of ERPs with IT or IQ, because these correlations have been found with measures on earlier epochs of the ERP. Similarly, the analyses presented by Caryl and Harper (on the same data as reported by Caryl, 1994) showed that task difficulty only affected the ERP after about 200 ms. Even though Caryl and Harper were concerned with pitch discrimination tasks as well as IT, their conclusions were made in general terms as follows: "the early ERP waveform is likely, therefore, to be affected by the difficulty of the task presented to the participant. For example, changes in P200 and P300 amplitude that reflect variation in task difficulty could affect the ERP ... one simple way to circumvent this problem is to present stimuli at the participant's previously measured threshold, thus equating task difficulty across participants. *Choice of an appropriate threshold accuracy may be important in such designs*" (Caryl & Harper, 1996, p.19 [italics added]). This conclusion may be overstated. For the IT task, the difference in P200 peak amplitude, over three levels of task difficulty, was not significant. The point made about an appropriate threshold accuracy also raises a question about the effect of task difficulty on ERPs—that is, are the ERPs different for correctly made discriminations than for incorrectly made discriminations? To explain: because threshold is arbitrarily defined at, for example, 75, 85 or 90% accuracy, then when trials are presented at such a threshold for ERP recording, errors will be made on about 10 to 25% of trials. It is possible, therefore, that the effect of task difficulty on ERP waveform, referred to by Caryl and Harper, results from differences in waveform associated with correctly and incorrectly discriminated trials. In any case, though, the effect appears to be confined to an epoch of the ERP (i.e., in the region of the P300) where correlations between ERP measures and IT or IQ have not been found. Appendix III to this thesis describes an experiment that goes some way to addressing this point about the effect of task difficulty on ERPs from the IT task. The conclusion reached on the basis of this experiment was that ERPs recorded during IT estimation, by adaptive staircase procedures, will not be affected by confounding of task difficulty with threshold as long as EEG epochs recorded to very easy trials (i.e., if trials with SOAs that are more than about 30 ms longer than the IT estimate) are excluded from averaging.

The conclusions drawn by the authors of these studies on ERPs and IT, about what processes IT measures and how individual differences in these processes might be reflected in differences in IQ, are now discussed.

5.6.4 Conclusions drawn from ERP studies on IT and IQ

Five of the papers under discussion reported research conducted at Edinburgh University (Zhang et al., 1989a; 1989b; Caryl, 1994; Caryl et al., 1995; Caryl & Harper, 1996). Two others were separate reports on one set of data (Morris & Alcorn, 1995; Alcorn & Morris, 1996). The final study (Colet et al., 1993) was on the relationship of data from auditory oddball ERPs and IT. The papers by Morris and Alcorn did not interpret their results in specific terms. Rather, they offered their correlational data as support for the position of the Edinburgh group on the importance of P200 on one hand, and as suggesting that ERP studies on IT might be integrated into the cognitive psychophysiology literature on P300, on the other hand. These two papers will therefore not be considered further.

Zhang et al.'s (1989a) rationale posited three alternative possible outcomes. These were that IT would correlate with either: P200 latency and rise time; with P300 latency; or with the difference between P300 and P200 latencies. These alternative outcomes would imply (according to the rationale of Zhang et al.) that IT indexes encoding of information, or encoding and evaluation of information, or evaluation of information, respectively. Zhang et al.'s results were consistent with the first possible outcome (i.e., IT is a measure of speed of encoding of information). Zhang et al. (1989b) provided support for this finding. They also reported a correlation between P200 and IQ. This latter finding provided a link between speed of encoding of information, IT, and IQ which was of course entirely consistent with Brand's (Brand, 1984; Brand & Deary, 1982) position on IT, as discussed in 5.2 (above).

Caryl (1994) identified the latency range 100 to 200 ms post-stimulus as being critical to understanding the correlation between IT and IQ. Caryl (p.41) discussed previous research that had implicated processes occurring in this latency as being involved in: the identification of visual stimuli; the allocation of processing resources; this latency range is where attentional influences are seen in ERPs. Following Zhang et al. (1989a, 1989b), he also pointed to these findings as implicating "basic aspects of stimulus processing" in individual differences in IQ.

Colet et al. (1993) interpreted their finding of correlations between IT and P200 rise time and P300 latency as providing support for a model that proposed that IT indexes stimulus evaluation time (seen in the relationship with P200 rise time). The correlation with P300 latency arises, according to their model, because this latency indexes 'context updating speed'. This model and interpretation are therefore largely consistent with Zhang et al.'s. and Caryl's interpretations of their data.

The next section will consider some of the assumptions that underlie these interpretations on ERP correlations with IT and IQ.

5.6.5 Some assumptions underlying the interpretation of ERP studies on IT and IQ

The most crucial assumption underlying the interpretations (as outlined above) of the correlations between ERP measures and IT (and the linkage of these correlations to individual differences in IQ) is that *the timing of the deflections of the ERP waveform* (e.g., the P200 and P300) *reflects the timing of activity in neuronal populations* whose activity is 'seen' in the ERP waveform. As Coles and Rugg (1995) explain, there is a problem with this assumption—"an ERP peak with a latency of 200 ms, might reflect the activity not of a single neural generator maximally active at that time, but the combined activity of two (or more) generators, maximally active before and after 200 ms, but with fields that summate to a maximum at that time" (p.10). This is the problem of component overlap. That is, the voltage seen at a particular electrode at a particular time may result from the activity of different, spatially separated generators with temporal characteristics that bear no simple relationship to the activity seen at the scalp site.

If the assumption that the ERP deflection reflects the activity of neuronal populations active at the time the deflection appears at the scalp is taken as met, then another crucial assumption operates in the interpretation of the relationships between P200, P300 and IT. This assumption was made explicit by Zhang et al. (1989a) but is common to all of the studies under consideration. It requires that if a psychological process has been associated with some measure of an ERP deflection, then a finding that the same ERP deflection (or more correctly, *what is assumed to be the same ERP deflection across studies*) changes, or is associated with yet another psychological process or measure, means that the action of the first psychological process is implicated in the second. Thus, by way of relevant explication, a finding reported by Chapman, McCary and Chapman (1978) that P200 "may reflect the process of encoding information from a sensory register into STM" (Zhang et al., 1989a, p.380), together with a finding that P200 correlates with IT, is taken to mean that IT is a measure of encoding information from a sensory register into STM. The same rationale was applied to the 'psychological meaning' of P300 found in the studies under consideration. A problem here is that, under different experimental conditions, what appears to be the same ERP deflection (e.g., P300) may be the reflection of the activity of different neural populations that are in turn associated with different psychological processes. To put it another way, the assumption is made that the same neural processes are being reflected in ERP deflections, even when they are found under different experimental conditions. In terms of the logic of making inferences from physiological data on psychological processes this form of reasoning is flawed because, in essence, it attempts to argue through the invalid process of 'affirming the consequent' (Cacioppo & Tassinary, 1990, p.15).

This is not to say that Zhang was wrong but rather that alternative inferences are possible. In more general terms, the interpretations of the correlations of ERPs with IT and IQ arise from a view of brain function that could be termed 'bottom up'. In other words, the assumption is being made that the sequence of ERP deflections corresponds with an hypothesised sequence of brain processing in which information passes from one stage to another without any modulation of the earlier stages by the outcome of 'analysis' at a later stage. However, the widely accepted view is that the brain processes information by parallel distributed pathways, and that these pathways involve feedback processes so that there really is no 'beginning' or 'end point' in the processing of information (Goldman-Rakic, 1988, provided the seminal demonstration and discussion on this argument). The question arises, then, as to whether a different interpretation of the correlations reported by Zhang et al. (1989a, 1989b) and Caryl (e.g., Caryl, 1994) is possible on the basis that the rise times of ERP deflections reflect a general but fundamental brain process that may relate to global efficiency of processing of information in the brain.

Chapter 6 of this thesis describes the development of a model whereby the rise times of ERP deflections reflect the efficiency of the recruitment of neuronal populations to firing. In turn, the efficiency of neuronal recruitment is hypothesised to be a process that may underlie brain efficiency of information processing and hence be causally prior to individual differences in cognitive abilities. The initial impetus for the development of this model came from an analysis of Reed and Jensen's (1992) paper on nerve conduction velocity and IQ. That paper and the model eventually developed on rise time measures of ERPs, along with hypotheses generated from the model, are described in Chapter 6. Chapter 7 describes an experimental test of those hypotheses.

Chapter Six: ERP rise times and cognitive abilities—a model

6.1 Preamble

Chapter 6 describes a general model that was developed to account for the reported relationships of ERP rise times with both IT and IQ. The development of this model was inspired, in part, by an examination of Reed's (1984, 1988) theory on the neurophysiological basis for the heritability of vertebrate intelligence. In a series of papers Reed and Jensen (1989, 1991, 1992, 1993a, 1993b) provided evidence in support of Reed's theory. Reed's theory and some of the evidence presented in support of it are discussed in the next section of this chapter.

Following discussion of Reed and Jensen's methodology and findings, a new model based on rise time parameters derived from short latency VERP deflections is presented. Whereas, as will be discussed shortly, Reed and Jensen (1992) sought to estimate nerve conduction velocity within the central nervous system by using ERP measures, the model proposed here argues that it is neuronal recruitment time that is more plausibly estimated from ERP measures.

The new model proposes that rise times of short latency ERP deflections reflect neuronal recruitment time. It further proposes that efficiency of neuronal recruitment is a feature of individual brains that underlies the efficiency of neural processing of information. Because efficiency of neural processing of information is thought to contribute to individual differences in cognitive abilities, ERP rise times may therefore prove to be a reliable correlate of measures of cognitive ability. Hypotheses derived from the model about the relationships between visual ERP rise times and cognitive ability are discussed. Chapter 7 reports an experiment designed to test these hypotheses.

6.2 Reed's theory on intelligence

6.2.1 The theory

Reed (1984, 1988) was concerned with possible mechanisms for the heritability of intelligence in vertebrates. He argued that speed of transmission of action potentials "along nerve fibers (dendrites and axons)[32] and across synapses between nerve cells" was a characteristic that plausibly was under genetic control and which "must affect speed of information processing" (1988, p.430). Reed's position was that the heritability of intelligence in humans, rests on variability in speed of information processing which, he argued, rests on variability in speed of transmission of action potentials.[33]

Reed developed his argument further by considering visual reaction time (RT; Reed. 1988, pp.431-432). He partitioned simple RT (with a mean value of about 300 ms in normal subjects) into three stages: input time, by which he meant transmission of stimulus information from the retina to the visual cortex; cortical conduction time, by which he meant all processing in the cortex relating to the initial stimulus; and output time, meaning the time for conduction of nerve impulses from the motor cortex to the hand. His estimate of the cortical conduction time stage of RT was about 200 ms.

Cortical conduction time itself, according to Reed, consists of what he termed "dendritic conduction time" and axonal conduction time. He argued that both of these processes operate on the same time scale (to within an order of magnitude) within the brain.

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[32] It is not entirely clear what Reed meant here. Transmission of action potentials along dendrites (if it occurs at all, which is an open question) does not occur in the same way as axonal conduction of action potentials. The current author has interpreted Reed's statement to mean the interaction of excitatory and inhibitory post synaptic potentials on dendritic membranes. This process of neural integration of synaptic inputs is the basis of the recruitment of neurons to firing (see below).

[33] The current author has interpreted this statement to mean inter-individual variability in the speed of transmission of action potentials. Within an individual, such variability would depend on axonal diameter—the greater the diameter, the faster the transmission. The same relationship applies between individuals; however, Reed (1988) also mentioned other possible determinants of axonal transmission speed, for example, differences in myelination properties.

Reed (1988, p.434) presented evidence in support of his argument that both dendritic and axonal conduction times are heritable and that therefore their sum, which he termed brain processing time, is also heritable. Reed noted that both dendritic conduction and axonal conduction processes should be considered when seeking to understand the heritability of intelligence.

6.2.2 Reed and Jensen's tests of Reed's theory

Reed and Jensen (1991, 1992, 1993a, 1992b) reported the results of a large scale study designed to test some aspects of Reed's theory (as outlined above). Not all aspects of their reports are directly relevant here and so some of the methodologies and findings will be mentioned only briefly. The most directly relevant aspects of the work to be discussed centre on Reed and Jensen's use of ERPs to derive estimates of nerve conduction velocity (NCV) within the brain. While these estimates were of subcortical NCV, it was argued by Reed and Jensen that they should correlate highly with cortical NCV and therefore with measures of speed of information processing and IQ.[34]

Reed and Jensen's sample consisted of 205 male post-secondary students, aged between 18 and 25 years. Various of the results reported were based on subsamples, ranging in size from 130 to 205 subjects. There are two aspects of the study program that should be differentiated. The first concerns the *measurement* of NCV in the peripheral nervous system (specifically, measurement of NCV in the median nerve of the arm). The second concerns the *estimation* of NCV within the brain from ERP data. The first of these is straightforward. This is because, essentially, it involves attaching electrodes to the skin of the arm, applying

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[34] Reed and Jensen offered no argument as to why this relationship should hold. It could be argued that NCV would be a general property of the brain. But, on the other hand, much of the activity flow in the cortex involves radial flow through columns of neurons (i.e., local circuits) rather than through longer distance cortico-cortical connections. Therefore, the notionally measurable subcortical NCV may not relate meaningfully to transmission in the cortex.

electrical stimulation at, for example, the wrist and measuring the time taken for the nerve impulse to arrive at the elbow or at the axilla. Given good technique, this NCV measurement is accurate and reliable (De Lisa, Lee, Baran, Lai & Spielholz, 1994). However, the second aspect is not straightforward for several reasons. Among these reasons are anatomical considerations, functional considerations, and methodological considerations. For these reasons, the brain NCV estimates may include processes over and above axonal conduction time. These issues will be canvassed more fully in the discussion that follows the summary of Reed and Jensen's results.

Reed's theory (as discussed above) makes several predictions on the relationships of NCV, RT and IQ. Essentially, if speed of information processing (within the cortex) depends on dendritic conduction times and axonal conduction times then RT should be correlated with both of them. Given that there is evidence that RT and IQ are correlated and that this correlation is thought to arise from the dependence of both measures on speed of information processing then IQ should also be correlated with both dendritic and axonal conduction times. Because, as discussed above, axonal conduction time (NCV) is reliably measured in the peripheral nervous system Reed and Jensen (1991) and others (e.g., Barrett, Daum & Eysenck, 1990; Vernon & Mori, 1992) have investigated correlations of these NCVs with RT and IQ.

The first report from Reed and Jensen (1991) concerned the relationship between NCV in the median nerve of the arm and each of: estimated visual pathway NCV; RT; and IQ. The sample size was 200. Data were reported for two groups from this sample: community college students and university students. These groups differed significantly on IQ, the latter group scoring higher. Correlations between arm NCV and estimated visual pathway NCV, RT and IQ were not significant.

The second report (Reed & Jensen, 1992) concerned visual pathway NCV (as estimated from visual ERPs) and IQ. Therefore, this paper will be described more fully. The rationale for this experiment rested on the assumption that, when studying the response of the visual system, "almost all of the latency between the retina and the PVC [primary visual cortex] is nerve conduction time" (p.260). Reed and Jensen stated that their study was the first to record short latency VERP responses from electrodes placed over the visual cortex with a sample of normal subjects. They discussed some evidence from clinical and retarded samples which suggested that VERP latency was inversely related to IQ. The VERP procedure that had been used in these studies and which was adopted by Reed and Jensen was chequerboard pattern reversal stimulation. (The VERP recorded to chequerboard pattern reversal stimulation will be discussed more fully below). Reed and Jensen described this VERP as consisting of two cortically generated deflections referred to as the N70 and P100 with latencies of about 70 and 100 ms, respectively. The former was said to represent the earliest response of the primary visual cortex to pattern reversal stimulation.

The sample size was 147 (72 community college students and 75 university students). The former group completed the PM and the latter group completed the APM. Scores were converted to equivalent Otis-Lennon IQ scores. EEG was recorded from Oz, Fz, and Cz; subjects were grounded via an electrode attached at Fpz (see Figure 3.1, in Chapter 3); band pass filters were set 2 - 100 Hz. Two channels of EEG were recorded: Oz referred to Fz; and Cz referred to Fz. The difference between these channels, representing a montage equivalent to Oz referred to Cz, was used for construction of ERPs. Stimuli were black and white chequerboard patterns (squares with a side subtending a visual angle 43′ at the viewing distance of 1 m) presented on a video monitor and reversing at 2 Hz. Latencies of N70 and P100 were measured. Two visual pathway NCV estimates (designated V:N70 and V:P100, respectively) were calculated by dividing the subject's head length by the relevant latency.

Table 6.1 reproduces Reed and Jensen's (1992) correlational data. Features of these data to note are: the significant correlations between the visual pathway NCV estimates and IQ; the significant correlation between P100 latency and IQ; the high correlations between ERP latencies and the corresponding derived NCV estimates; and the relatively modest, given that they are estimates of the same velocity, correlations between the two NCV estimates and between the two ERP latency measures.

Reed and Jensen (1992) explicitly described their experiment as an attempt "to estimate directly one of the determinants (brain NCV) of information-processing speed and to correlate it with intelligence" (p.266). They also suggested that other factors (e.g., brain design, synaptic transmission speed) which may directly or indirectly determine speed of information processing are not amenable to noninvasive estimation using currently available technology.

Table 6.1

Correlations among IQ scores, VERP latencies and derived visual pathway NCVs in 147 subjects (from Reed & Jensen, 1992)

	IQ	N70 latency	P100 latency	V:N70 NCV
N70 latency	−.117			
P100 latency	−.212 *	.389 **		
V:N70 NCV	.184 *	−.823 **	−.296 **	
V: P100 NCV	.256 **	−.185 *	−.714 **	.525 **

Note. Source: Reed and Jensen (1992, Table 3, p.265; reproduced with permission of the publisher).

* $p < .05$; ** $p < .01$, two-tailed.

The third paper in this series (Reed & Jensen, 1993a) was concerned with latencies of somatosensory ERPs. These ERPs were recorded at the scalp in response to stimulation of the median nerve of the arm. These ERPs have very short latencies (typically less than 20 ms). Two of the deflections, N19 and P22, were described as representing responses at the thalamus and at parietal sensory cortex, respectively (p.448). The difference in latency between these two deflections was therefore taken to represent conduction time between the thalamus and the cortex. The sample size was 130. Correlation of the P22–N19 latency difference with IQ (equivalent Otis-Lennon, see above) was –.217 ($p < .05$, two-tailed). This result was therefore consistent with predictions based on Reed's (1984, 1988) theory.

The final paper in the series based on this large sample (Reed & Jensen, 1993b) examined the correlations between choice RT measures, visual pathway NCV estimates, and IQ. The sample size was 147 (i.e., the same sample described in Reed & Jensen, 1992). It was found that while both of the former measures correlated with IQ, they did not correlate with each other. This finding was interpreted as being plausibly consistent with the proposition that "there may be two largely independent neurophysiological mechanisms affecting intelligence levels in normal persons" (p.193). Reed and Jensen suggested that more intelligent individuals exhibit higher cortical NCV, as demonstrated by the correlation of visual pathway NCV estimates with IQ. Additionally, they also suggested that more intelligent individuals have shorter cortical processing pathways, as demonstrated by shorter choice RT (amongst other more complex RT measures). Again, these findings were consistent with Reed's (1984, 1988) theory.

These findings, which support predictions based on Reed's theory, are obviously very important. The sample size was large (though restricted in range on ability) and there appears to be a consistent pattern of relationships between measures of speed at the physiological level (i.e, visual ERP latencies and the derived visual pathway NCV, as well as the somatosensory ERP latency), behavioural measures of speed (i.e., various RT measures), and IQ. The following critique of the rationale for the estimation of the visual pathway NCV seeks to broaden Reed and Jensen's approach by taking account of problems in their interpretations and raises the possibility that other brain processes can be estimated via the ERP. Specifically, it will be argued that visual ERP latency, while obviously a measure of speed of processing, cannot be considered to be mainly nerve conduction time (as was required by Reed and Jensen's, 1992, rationale). The implication of this argument is that it is not nerve conduction velocity that is being estimated by Reed and Jensen's procedure. Rather, it is a measure of VERP latency corrected for head size. This measure is, of course, a measure of speed of processing. This interpretation is consistent with the fact that evaluations of clinical data on pattern reversal ERPs recommend the adoption of different normal ranges of latencies for males and females because of gender differences in head size (e.g., Allison, Wood & Goff, 1983, p.630-631).

6.2.3 Critique on Reed and Jensen's 'subcortical NCV' methodology

As noted in the introduction to the discussion on Reed and Jensen's work, there are at least four reasons why their use of visual ERP latencies to estimate visual pathway NCV is not straightforward.

The first reason is based on a consideration of some functional properties of the visual pathways. To explain: the estimation of visual pathway NCV from visual ERP latency requires the assumption that the pathway from retina to visual cortex is, in effect, a unidirectional pathway. That is, the effect of a stimulus impinging on the retina is taken to be the propagation of nerve impulses along the visual pathway to the visual cortex from whence they are passed on for higher processing. However, there is evidence that visual processing is not so straightforward. For example, there are more projections 'back' from the visual cortex to the thalamus than there are 'forward' from the thalamus to the visual cortex and there is evidence that these projections exert feedback control from the visual cortex on activity in the lateral geniculate bodies (Sillito, Jones, Gerstein & West, 1994). It is recognised that such a consideration should not affect the very first response of the cortex to the afferent input but it may affect the later responses (i.e., P100). At a different level, the notion of information passing from the visual cortex to higher processing stations needs to be tempered by cognisance of the interconnectedness of areas within the visual cortex and of extrastriate (i.e., from outside the visual cortex) cortical input to the visual cortex (Regan, 1989, p.309). It is plausible that these projections act as modulators of activity within the visual cortex and visual pathway and that this modulation reflects the effects of activity within the visual pathway itself. These types of considerations are consistent with the point made in Chapter 5 that these feedback processes mean that there is no simple beginning or end point in brain processing. In other words, the assumption that ERP latency solely reflects NCV may be an oversimplification because the delay from retina to visual cortex may not be a constant that is solely dependent on axonal conduction of action potentials.

The second reason is methodological. The chequerboard pattern reversal ERP and the cortical origins and characteristics of the deflections recorded are not as simple as the description given by Reed and Jensen (1992) might have implied. This pattern reversal ERP procedure has been extensively studied and it is the ERP methodology of choice in clinical applications on the visual system (Chiappa, 1990; Halliday, 1978; Halliday, Barrett, Carroll & Kriss, 1982; Regan, 1989). Factors that influence pattern reversal ERP latency are well known and include the luminance of the stimulus, cheque size, and sex and age of subject. None of these factors directly affected Reed and Jensen's results because they had a sample that was homogeneous with respect to age and sex and they held cheque size and luminance constant. However, the point is that if they had used differently configured stimuli then their estimates of NCV would have been different (although correlations of these estimates with IQ would be unaffected if linear relationships were involved) because, at the very least, retinal transduction time would be different.

The third and fourth reasons are anatomical. The visual pathway consists of the retinal receptors and ganglionic cells, the optic nerves (which unite and cross at the optic chiasm then proceed as the optic tracts), the lateral geniculate bodies of the thalamus (there are also projections to the superior colliculus), and the optic radiations (which terminate in the visual cortex). At even the most basic level of analysis, this complexity renders simple interpretation of visual ERP latency as NCV problematic. This is because structurally, the optic nerve, the visual tract and the optic radiation vary in terms of the diameter of the axons involved. This difference means that axonal conduction velocity will vary along the pathway. Conduction velocity will be fastest in the optic nerve and tract, which are of larger diameter, and will be slowest in the optic radiation which is of smaller diameter. Retinal transduction time was treated as a constant in Reed and Jensen's rationale. The validity of this is an open question.

Reed (1988), as discussed above, pointed out that not only was axonal conduction time likely to be important in determining speed of information processing but that what he termed "dendritic conduction time" was likely to be equally as important. The rationale for estimating NCV explicated by Reed and Jensen (1992) was concerned with axonal conduction time and also explicitly argued that synaptic transmission time in the visual pathway takes less than 3 ms (p.260). That is, it was concerned with the rate of axonal propagation of action potentials. As described above, the rationale implicitly assumed that the visual pathway is unidirectional and hence no account was taken of the fact that neurons in the visual pathway are the recipients of both afferent and cortical input which will include feedback influences and this means that dendritic processes (see Footnote 32, above) should be considered. The implication of this is that the recruitment time involved in the firing of neurons is a process that should be accounted for in the overall latency between retinal stimulation and cortical response. A model for relationships between brain function and cognitive abilities based on neuronal recruitment time is described next.

6.3 Neuronal recruitment time and efficiency of brain processing: A model

Following the above discussion, it is argued here that Reed and Jensen (1992) have not taken account of what is a fundamental property of neural functioning—that is, recruitment time involved in the firing of neurons. To explain: whether a neuron within the central nervous system fires or not depends on the integration of converging inputs (both excitatory and inhibitory) from other neurons. In the case of neurons in the visual pathway, this is so for both afferent input and for cortical input. Converging inputs synapse on both the dendrites and on the cell body of a target neuron. The rate at which converging inputs on the neuron cumulate their activity to raise the nett membrane potentials to the threshold firing levels may reflect a design feature of individual brains that may relate to functional efficiency: more concentrated recruitment would lead to earlier and more reliable firing in each station in a neuronal circuit and thus to faster, more reliable activity in the circuit overall. It is these processes, then, that Reed (1988) may have meant when he referred to the dendritic conduction component of brain processing time. The question arises as to how these processes might be manifested in the ERP record of brain activity.

Because, as is generally accepted, gross electrical records at the scalp reflect postsynaptic fields, then the proposition here is that the rise times of the early VERP deflections reflect neuronal recruitment time for populations in the visual cortex. This is because, as Reed and Jensen (1992) argued, the deflections measurable in these VERPs are the result of simple sensory information arriving at the visual cortex.[35] If the rise times of the

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[35] Reed and Jensen (1992) assumed that the N70 and P100 deflections arise from the response of the *primary* visual cortex (i.e., Area 17). This assumption was supported by the citation of a study by Fox, Miezin,

early ERP deflections reflect recruitment of neuronal populations, and speed of neuronal recruitment is taken to be an aspect of overall brain efficiency, then it follows that ERP rise times will be an index of brain efficiency. It may be that variations in this efficiency underlie differences in higher cognitive abilities. An advantage of using such a measure of brain efficiency is that it can be applied to ERP deflections that represent the earliest response of sensory cortex. That is, it would be a measure of a lower level characteristic of cortical response that may also underlie efficiency of higher functions within the cortex.

The basic premise of the model is that the rise time of the short latency deflections of the pattern reversal VERP will provide an index of recruitment time as outlined above. The rise time measure can be derived from the same experimental procedure employed by Reed and Jensen (1992) but may relate to a characteristic of brain structure and function that may be a fundamental determinant of efficiency of information processing. Reed and Jensen's estimate of visual pathway NCV derived from ERP latency. It is argued here that ERP latency (at least for the deflection representing the earliest response of sensory cortex) may be divided into an axonal conduction stage and a neuronal recruitment stage and it may be the neuronal recruitment stage that gave rise to the correlations with IQ found by Reed and Jensen.

Allman, Van Essen and Raichle (1987). The Fox et al. study was concerned with the retinotopic organisation of primary visual cortex. The stimuli used were chequerboard patterns (i.e., consistent with those used by Reed & Jensen) and the results presented (based on PET scans) showed strong response to these patterns in primary visual cortex. However, this does not constitute direct evidence that the N70 and P100 are generated in the primary visual cortex. There is evidence, from a study which used both PET and ERP techniques (Heinze et al., 1994), that P1 (of visual ERPs recorded during a visual selective attention task) is generated in extrastriate areas. This does not necessarily mean that P100 to pattern reversal is generated in these same areas. Indeed, two of the authors of this research explicitly make this point in an earlier report (Mangun, Hillyard & Luck, 1993, p.239). Recent research on the event-related magnetic fields to pattern reversal stimulation (Nakumara et al., 1997) suggested that components with latencies of about 70 ms and 100 ms do originate in the striate cortex (near or around the calcarine fissure). As far as the model proposed here is concerned, it is hypothesised that responses in striate and extrastriate cortex would show the predicted effect because they are taken to constitute early sensory responses.

While there are good reasons for adopting the chequerboard pattern reversal ERP methodology in terms of the reliability with which the characteristic deflections are elicited in nonclinical populations (Chiappa, 1990), the model outlined above requires that rise times of early sensory ERPs in any modality should reflect neuronal recruitment. Therefore, for example, the early deflections in ERPs recorded to flash stimuli such as those presented during IT estimation, when recorded from occipital electrodes, should reflect neuronal recruitment time. Similarly, ERPs recorded to simple tone pips should reflect equivalent processes. It is also argued that the P200 rise time measure recorded from Cz by Zhang et al. (1989a, 1989b) and Colet et al. (1993), and the slope and gradient measures of Caryl (e.g., 1994) and Morris and Alcorn (1995) reflect neuronal recruitment time. However, the longer latency of the P200 deflection may mean that the nexus with the earliest cortical responses of sensory processing is broken. Nevertheless, the relationships reported by these workers between their ERP measures and cognitive abilities and IT can be interpreted as reflecting the relationship between efficiency of neural recruitment (incorporating cortical feedback processes) and the expression of that efficiency in the completion of tasks of some complexity.

A series of hypotheses on the relationships of ERP rise times to cognitive abilities follow logically from the model outlined. These are discussed next.

6.4 Hypotheses derived from the model and other hypotheses to be tested

At the outset, it should be recalled that in Chapter 5 it was argued that a better understanding of the relationship of IT to cognitive abilities would be result when the psychometric tests used are measures of (markers for) broad second order abilities. It was also argued that this is true for understanding the relationship of ERP measures with cognitive abilities and IT. It was therefore concluded that cognitive abilities should be operationalised in terms of Gf–Gc theory, and specifically by using tests from the WJ-R.

The information processing hierarchy described in Gf–Gc theory can incorporate the ERP measures derived from the model described in the previous section (i.e., the rise time and latency measures). In terms of information processing capacities, Gf–Gc theory proposes a hierarchy of separate capabilities, with sensory detector capabilities at the foot of the hierarchy, association processing capabilities at the next level, perceptual organisation at the next level, and relation eduction at the top of the hierarchy. The measure of the ERP derived from the neural recruitment model of brain efficiency (i.e., the rise time of the short latency deflections of the ERP) is held to be a direct measure of sensory detector capabilities; the latencies of occipitally recorded deflections (when corrected for head size) may also be measuring these sensory detector capabilities. This is because, as described above, these deflections are taken to represent the earliest responses of sensory cortex. These capabilities are therefore predicted to underlie performance on tasks such as inspection time (IT). It is predicted, therefore, that the ERP measures are correlates of IT and, further, that ERP measures and IT will in turn be correlates of measures of association processing capabilities (Gs and Gsm), perceptual organisation (Gv) and relation eduction (Gf and Gc). Specific hypotheses are:

Hypothesis 1 concerns the relationship of IT to the constructs described in Gf–Gc theory. The rationale for this hypothesis was discussed at length in Chapter 5.

1. IT is inversely related to tests of Gs and Gv. It is predicted that IT will not correlate with tests of Gf or Gc.

Hypothesis 2 has two parts and concerns the relationships of the ERP rise time measures with IT and with tests from the WJ-R.

2(i). Rise times of the early deflections in ERPs recorded from occipital derivations for chequerboard pattern reversal ERPs and for ERPs recorded during IT estimation correlate positively with IT.

2(ii). The rise times measures [as described in 2. (i)] correlate negatively with scores on WJ-R. Specifically, these ERP measures will show correlations with tests for Gs, Gsm and Gv rather than with tests for Gf and Gc.

That is, short rise times (reflecting efficient recruitment) are associated with short IT. Note that these hypotheses relate specifically to ERPs recorded from occipital electrodes. As far as possible, given the volume conduction properties of brain tissue and the skull, these placements allow the assumption that the ERP deflections are generated in the visual cortex. This means that the rise time measures can be taken to reflect recruitment of neural populations in response to visual stimulation. That is, the efficiency measure is being indexed at a primary level of cortical response. The second part of the hypothesis follows from the discussion of the information processing hierarchy described by Gf–Gc theory.

Hypothesis 3 has two parts and is concerned with the latencies of ERP deflections. The position taken here on Reed and Jensen's (1992) subcortical NCV estimates is that they are best understood as measures of ERP latency corrected for head size. Given this, the rise time measure is incorporated into the latency measure and therefore they should be positively related to each other.

3(i). The rise time measures will be positively correlated with ERP latency. (This means they will therefore be negatively correlated with NCV [as defined by Reed and Jensen]).

Following this prediction, the ERP latencies are also predicted to show the same pattern of correlations with IT and scores on WJ-R as the ERP rise time measure. This prediction is consistent with the findings of Reed and Jensen (1992; see Table 6.1 in this chapter).

3(ii). The ERP latencies recorded at occipital sites will be positively correlated with IT. These latencies will be negatively correlated with tests from the WJ-R measuring Gs, Gsm and Gv rather than with tests for Gf and Gc.

Hypothesis 4 has several parts and is concerned with the P200 deflection from ERPs recorded during IT estimation and with all deflections recorded at non-occipital sites.

4(i). The P200 rise times will be positively correlated with IT and negatively correlated with WJ-R scores (as described in Hypotheses 2 and 3).

4(ii). P200 latency will be positively correlated with IT and negatively correlated with WJ-R scores (as described in Hypotheses 2 and 3).

4 (iii). Rise times and latencies of earlier deflections recorded at non-occipital sites will be positively correlated with IT and negatively correlated with WJ-R scores (as described in Hypotheses 2 and 3).

The various parts of this hypothesis were discussed in 6.3. Part (i) arises from the prediction that findings on P200 relationships with IT and cognitive ability can be accounted for by the model proposed here and therefore the predicted relationships are consistent with previously reported results (e.g., Zhang et al, 1989b). Part (ii) follows from part (i) and is consistent with the relevant arguments discussed in the previous sections. Support for these two parts of Hypothesis 4 would provide an explanation for previously reported results in terms of the model of brain function proposed here. Part (iii) extends the predictions on the rise times and latencies to early non-occipital deflections (see Hypothesis 3).

6.5 Summary of Chapter 6

This chapter described the development of a model on one feature of neural efficiency that may underlie efficient processing of information within the brain. It is thought that such efficient processing may be related to higher cognitive abilities. Reed and Jensen's

(1992) study which attempted estimation of visual pathway NCV was reviewed and it was shown how this work inspired the model presented here. Also discussed was the possibility that the model presented here could account for relationships found between ERP rise times and IT and IQ (as discussed in Chapter 5). Hypotheses derived from the model and other hypotheses on the relationships between ERPs, IT and cognitive abilities were presented. Chapter 7 will describe an experimental test of these hypotheses.

Chapter Seven: A test of the rise time model

7.1 Preamble

Chapter 7 reports the results of tests of the hypotheses presented and discussed in Chapter 6. All results are discussed as they are presented. The chapter concludes with a general discussion on the outcomes of the experiment.

7.2 Method

Subjects.

N = 64; 38 males and 26 females. Mean age was 26.2 (*SD* = 6.6) years. Subjects were recruited widely. Nineteen subjects were university students, with the remainder drawn from the wider community. A majority of the latter responded to an advertisement placed in a suburban newspaper. Subjects were paid A$20.

Apparatus and materials.

EEG recording

EEG was recorded in a lead-plated cubicle lit at an intensity of 35 lx. Amplification equipment and other hardware and software were as described in Chapter 3. Subjects were monitored via CCTV and contact was via a loudspeaker.

Pattern reversal ERP recording

EEG was recorded from Oz referred to Cz (International 10/20 system, see Figure 3.1). One channel of EOG was recorded from an electrode attached in the pupillary line just above the eyebrow of the left eye and referred to Cz. The subject was earthed via the right ear lobe. Amplifier gain was set at 10,000 with analogue filters set 0.2 - 100 Hz; the 50 Hz notch filter was not used in these recordings.

Chequerboard pattern reversal stimuli were presented on a video monitor. Black and white squares (10 mm on a side, subtending a visual angle of 34′ at the viewing distance of 1 m) reversed at a rate of 2 Hz. With the exception that the EEG recording here was from an actual montage of Oz–Cz (rather than from the difference between two channels equivalent to Oz-Cz), the recording details replicated those of Reed and Jensen (1992). There was a fixation point (a red, horizontal figure eight symbol [i.e., ∞]) in the centre of the screen.

IT estimation and concurrent ERP recording

EEG was recorded from O1, O2 and Cz (International 10/20 system, see Figure 3.1). One channel of EOG was recorded from an electrode attached in the pupillary line just above the eyebrow of the left eye. All electrodes were referred to the left ear lobe and the subject was earthed via the right ear lobe. Amplifier gain was set at 10,000 with analogue filters set 0.2 - 100 Hz; the 50 Hz notch filter was not used in these recordings.

IT stimuli were presented on a video monitor at a viewing distance of 1 m. The target figure consisted of two vertical lines 22 mm and 27 mm in length and joined at the top by a horizontal line 12 mm long. The shorter line appeared on the left or the right equiprobably. Following the exposure of the target figure it was immediately replaced by a "flash mask" (Evans & Nettelbeck, 1993) of 290 ms duration and consisting of two vertical lines 37 mm long shaped as lightning bolts (see Figure 1.1). The appearance of the target figure was preceded by the appearance of a small filled circle 4 mm wide in the area in which the subsequent target figure would appear; this acted as a warning cue. The duration of the warning cue was 425 ms and it was followed immediately by the target figure. The subjects signalled on which side of the target figure the shorter line had appeared by pressing the corresponding button on a bar that rested on the arms of the chair.

Cognitive abilities testing

The following tests from the WJ-R were completed: Memory for Sentences (Gsm), Cross Out (Gs), Visual Closure (Gv), Picture Vocabulary (Gc), and Analysis-Synthesis (Gf).

See Appendix II for details of these tests. All tests were administered in accordance with instructions in the manual.

Procedure.

Upon their arrival at the laboratory, the experimental procedures were explained to the subjects and any concerns raised were addressed. The aim of this familiarisation of the subject with the laboratory was to establish rapport between the experimenter and the subject and to put the subject as at ease as possible. Informed consent was affirmed by the subject via a standard protocol.

First, subjects completed the five tests from the WJ-R. These tests took about forty minutes to administer and were completed in the same order by all subjects. Next, subjects were prepared for EEG recording and, when seated comfortably in the recording cubicle, IT estimation commenced.

The IT estimation began with familiarisation with task requirements. Subjects then performed 10 trials with an SOA of 835 ms, 10 trials with an SOA of 418 ms and 10 trials with an SOA of 250 ms. Perfect performance was required at the first two SOAs and nine correct responses were required at the latter SOA, before the IT estimation procedure began. The estimation algorithm was an adaptive staircase procedure (Wetherill & Levitt, 1965) that returned an estimate at the 90% accuracy level. Two consecutive IT estimations were made. EEG recording during IT estimation proceeded as follows.

EEG recording epochs were 2.56 s duration, the sampling rate being 400 Hz. All EEG processing was done with SCAN software as follows. A 30 Hz low-pass filter with a slope of 24 dB/octave (–6 dB at 30 Hz) was applied. A prestimulus baseline was established for 500 ms prior to the onset of the warning cue. Next, an ocular artefact reduction algorithm

(Semlitsch, Anderer, Schuster & Presslich, 1986) was implemented.[36] This procedure was adopted in preference to excluding trials during which an eye blink had occurred because it was important that as many trials as possible be used to construct the ERPs, thereby increasing the signal-to-noise ratio.

In view of the outcome of the study reported in Appendix III, the following procedure was adopted for construction of the ERPs recorded during IT estimation. EEG recorded to trials with an SOA 20 ms, or greater, than the IT estimate of the subject were excluded from averaging. Effectively, this excluded the initial trials with SOAs ranging from 250 ms to about 120 ms which most subjects found very easy. However, the criterion was applied separately for each subject. EEG from both estimation procedures was averaged and one ERP was constructed beginning at the onset of the warning cue. This ERP will be referred to hereafter as the 'IT estimation ERP'.

Following IT estimation, pattern reversal ERPs were recorded. The subjects were told that the requirement for this task was that they focus on the fixation point, in the centre of the display, for about 30 s. (To ensure compliance with this task demand, subjects were informed that they would be monitored, during the recording, via CCTV). Subjects were told that as soon as the pattern ceased reversing they should look away from the monitor and await further instructions. Three consecutive presentations of 70 reversals were made with a 2 minute interval between presentations.

EEG recording proceeded as follows. EEG recording epochs were 366 ms duration, the sampling rate being 350 Hz. All EEG processing was done with SCAN software as

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[36] See Footnote 53, in Appendix III for details of the ocular artefact reduction algorithm. In this experiment, the standard deviations of the transmission coefficients SD(β) were required to be less than 0.01 μV or else the algorithm was not applied. For only one subject was this the case and in this instance EEG epochs containing eye blink artefact (i.e., voltage in the EOG channel exceeded ± 50 μV) were excluded from averaging. For one other subject, the ocular artefact reduction algorithm failed because the subject did not blink enough times during the EEG recording; again EEG epochs containing eye blink artefact were excluded from averaging.

follows. A 30 Hz low-pass filter with a slope of 24 dB/octave (–6 dB at 30 Hz) was applied. A prestimulus baseline was established for 50 ms prior to the reversal of the pattern. Next, any sweep in which the EOG amplitude exceeded ±50 μV (indicating eye-blink or movement) was excluded from averaging. Following this, each individual EEG sweep was reviewed for any artefact and, additionally, the sweeps immediately prior and subsequent to those rejected for eye artefact were also rejected. The reason for this was to produce an ERP record that was as 'clean' as possible so as to enable rise times to be measured as reliably as possible. One ERP was constructed to the reversal of the pattern. This ERP will be referred to hereafter as 'pattern reversal ERP'.

To enable comparison with data reported by Reed and Jensen (1992), their V:N70 and V:P100 measures (i.e., what they referred to as visual pathway NCV estimates) were calculated. This calculation requires an estimate of the length of the visual pathway. Reed and Jensen used cephalometer callipers to measure head length directly, which they then took as an estimate of the length of the visual pathway. Here, the distance across the top of the head from the nasion to electrode site Oz was measured with a tape measure (see Figure 3.1). The length of the visual pathway was estimated by assuming that this distance constituted a semicircle with a diameter equivalent to head length.

7.3 Results

7.3.1 Descriptive statistics

Descriptive statistics are presented first, followed by tests of hypotheses. Table 7.1 shows the means and standard deviations for the tests from the WJ-R.[37]

The sample was above average in ability but the distributions were relatively normal (Appendix IV shows the distributions of scores for each of the tests). Table 7.2 presents data

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[37] The WJ-R provides a variety of scoring strategies. The scores used in this thesis are deviation scores (mean = 100, *SD* = 15) based on age norms.

that address the question of how well the pattern of intercorrelations between tests for this sample correspond with the hypothesised factor structure of the WJ-R. Below diagonal of the table shows the correlations between tests for this sample; above the diagonal shows the residual when the corresponding correlation from the standardisation sample (McGrew et al., 1991) is subtracted from the correlation for this sample. As Table 7.2 shows, the sample data correspond well with the data from the WJ-R standardisation sample. Correlations were not significantly different from the standardisation sample correlations.[38] Only three of the correlations differed in magnitude by more than .10 from the correlations in the standardisation sample and all of these involved the test Visual Closure (Gv).

The mean of the average IT estimates for 64 subjects was 89.6 ms (*SD* = 17.7); the correlation between these estimates was .79, (p <.001, two-tailed). The corresponding estimate for the sample of 40 subjects (including 24 university students) reported in Chapter 3 was 81.7 ms (*SD* = 14.1). This difference ($t = 2.52$, df = 102, $p < .05$) is consistent with the broader ability range of the sample here.

Table 7.1

Means and standard deviations for tests from the WJ-R from 64 subjects

WJ-R test	Mean	SD
Memory for Sentences (Gsm)	109	17.3
Cross Out (Gs)	112	16.8
Visual Closure (Gv)	105	12.0
Picture Vocabulary (Gc)	110	14.0
Analysis-Synthesis (Gf)	110	16.3

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[38] This test was accomplished by treating the standardisation sample correlation as ρ and the sample here as a one-sample test of the null hypothesis that the obtained correlation equals ρ. Fisher's Z transformation was used along with Cohen's (1988, p.142) correction for the one sample test.

Table 7.2

Intercorrelations of WJ-R tests (below diagonal) and difference from corresponding correlation in the standardisation sample[a] (above diagonal)

	MS	CO	VC	PV	AS
MS		0.073	–0.241	–0.062	–0.058
CO	0.415 ***		–0.188	0.000	0.080
VC	0.018	0.205		0.153	0.003
PV	0.384 **	0.298 **	0.368 **		0.019
AS	0.393 **	0.429 ***	0.246 *	0.388 **	

Note. MS = Memory for Sentences; CO = Cross Out; VC = Visual Closure; PV = Picture Vocabulary; AS = Analysis-Synthesis

[a] The standardisation sample correlations used were for the age group 30 - 39 years which was the closest available comparison group for the sample here.

p* < .05; ** *p* < .01; * *p* < .001, one-tailed

Figure 7.1 shows the grand average pattern reversal ERP from 64 subjects. Table 7.3 shows the latencies and amplitudes for the N70 and P100 deflections (see Figure 7.1). The rise time measures for the P100 deflection were determined by subtraction of the relevant latencies (i.e., P100–N70). The N70 rise time was measured directly. To explain, the pattern reversal ERPs were such that a local minimum prior to the N70 could usually be identified (sometimes this was a P wave with a latency of about 50 ms) and this was taken as the starting point for the measurement of N70 rise time. The N70 and P100 rise time measures are shown in Table 7.3.

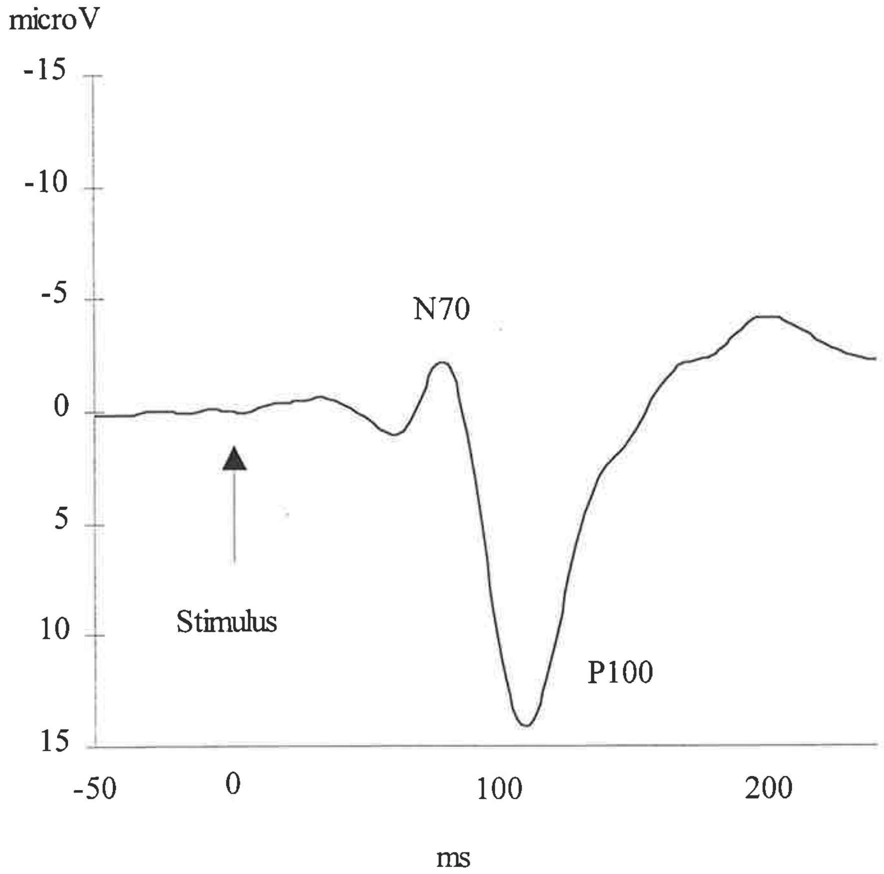

Figure 7.1 Grand average pattern reversal ERP at electrode site Oz from 64 subjects.

Table 7.3

Mean (and standard deviation) for latencies (ms), amplitudes (μV) and rise times (ms) of pattern reversal ERP deflections for 64 subjects

	Latency	Amplitude	Rise time[a]
N70	73 (8)	4.5 (3.9)	21 (5)
P100	101 (8)	9.3 (4.6)	28 (5)

[a] For N70 rise time $N = 63$. As described in the text, measurement of the rise time for this deflection required the identification of a local minimum preceding N70. In one case this was not possible.

Latencies for the P100 deflection are consistent with those reported in the literature (Allison et al., 1983; Chabot & John, 1986; Chiappa, 1990; Halliday et al., 1982; Reed & Jensen, 1992). There are no normative data available for the N70 but the value here is very close to that reported by Reed and Jensen (1992).

The mean head length (N = 64) was 208 mm (*SD* = 11); Reed and Jensen reported a mean head length of 200 mm (*SE* = .51). Their measure was certainly more precise; however, the measure here was reliable. The measure from nasion to electrode site Oz was repeated for 32 subjects (see below) and the correlation between the two measures was .95. The V:N70 and V:P100 measures (adopting Reed and Jensen's nomenclature) were 2.9 m/s (*SD* = .45) and 2.1 m/s (*SD* = .24), respectively. The values reported by Reed and Jensen were 2.77 m/s (*SD* = .15) and 2.00 m/s (*SD* = .09), respectively.

Figure 7.2 shows grand average IT estimation ERPs (at three electrode sites: O1, O2 and Cz) from 62 subjects[39]. Table 7.4 shows the latencies and amplitudes for the P1, N1 and P2 deflections (this nomenclature was adopted because the latencies of the deflections differ depending on which electrode site is considered). These deflections are marked in Figure 7.2.

The rise time measures for the N1 and P2 deflections were determined by subtraction of the relevant latencies (i.e., N1–P1, and P2–N1, respectively). These rise time measures are shown in Table 7.5. The P1 rise time could not be measured because it was not possible to determine a point (i.e., a local minimum) objectively from which to begin the measurement.

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[39] EEG data for two subjects' IT estimations were lost because of storage media malfunction.

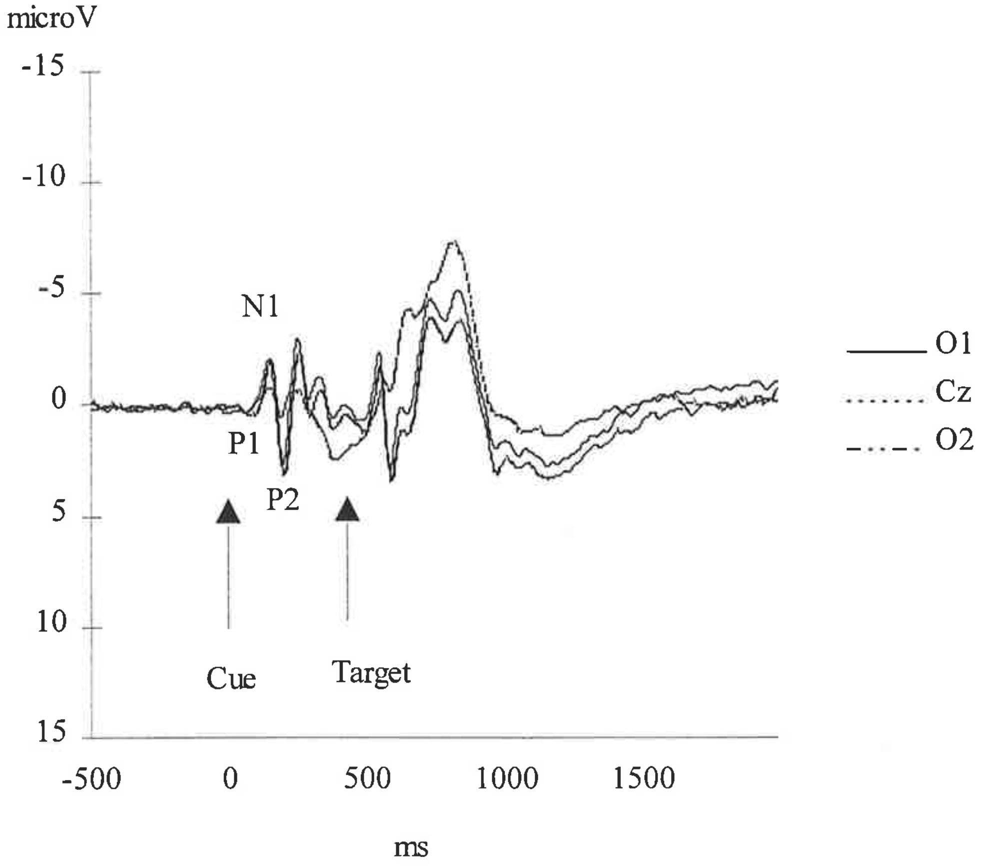

Figure 7.2. Grand average IT estimation ERP at three electrode sites from 62 subjects.

Table 7.4

Mean (and standard deviation) for latencies (ms) and amplitudes (μV) of ERP deflections for 62 subjects[a] at three electrode sites for IT estimation ERPs

	O1		O2		Cz	
	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude
P1	141 (13)	2.5 (2.3)	142 (12)	3.0 (2.6)	137 (18)	1.4 (2.4)
N1	190 (15)	3.6 (2.8)	193 (14)	3.8 (3.2)	172 (21)	1.5 (2.7)
P2	242 (13)	3.7 (2.5)	243 (12)	3.5 (2.7)	221 (23)	2.0 (2.7)

[a] The *N* varies slightly because in some cases a deflection could not be identified. The minimum *N* is 58.

Table 7.5

Mean (and standard deviation) for rise times (ms) of ERP deflections for 62 subjects[a] *at three electrode sites for IT estimation ERPs*

	O1	O2	Cz
N1	50 (12)	51 (12)	35 (19)
P2	52 (11)	49 (11)	49 (21)

[a] The *N* varies slightly because in some cases a deflection could not be reliably identified. The minimum *N* is 58.

Reliability of measures

No reliability measures are available from this sample for the WJ-R scores. According to the WJ-R technical manual (McGrew et al., 1991), test-retest reliabilities for the tests used here range from .83 to .93.

Regarding the measures from the ERPs, there are two issues of reliability that can be addressed. The first of these is the reliability with which ERP components can be identified and measured by the experimenter. The second is the stability of measures within an individual over time (i.e., over separate recording sessions). With respect to the first issue, ERP measures from the pattern reversal ERPs were logged on two separate occasions (the interval between the two measures was six weeks) by the author. Table 7.6 shows the correlations between the measures from the pattern reversal ERPs, on both occasions they were logged. These correlations are very high because the values are logged electronically after the deflection is identified.

Table 7.6

Correlations for pattern reversal ERP measures logged on two separate occasions

	Latency	Amplitude	Rise time
N70	.93	.99	.98[a]
P100	.99	.99	.80

Note: $N = 64$ except [a] $N = 63$. All $p < .01$.

With respect to the second issue, 32 of the subjects returned to the laboratory at intervals ranging from one week to about one year after their initial attendance. At this second session, pattern reversal ERPs were recorded, as described above. Table 7.7 shows the correlations between the measures from the pattern reversal ERPs on these two occasions.

Table 7.7

Test-retest correlations for pattern reversal ERP measures recorded on two separate occasions at intervals ranging from one week to one year for 32 subjects

	Latency	Amplitude	Rise time
N70	.91	.94	.68[a]
P100	.94	.78	.67

Note: $N = 32$ except [a] $N = 30$. All $p < .01$.

An important methodological issue regarding ERP rise time measures concerns their dependence or otherwise on the amplitude of the deflections from which they are measured. It was argued at some length in Chapters 1 and 4 that the amplitude of ERP deflections can be influenced by many factors (e.g., skull thickness, interelectrode impedance, stimulus intensity) unrelated to individual differences in brain activity. Therefore it was necessary to examine the intercorrelations of the rise time measures and amplitude measures. The correlations for the pattern reversal ERPs were .42 and .39 (both $p < .01$) for N70 and P100, respectively. Table 7.8 shows the correlations for the measures derived from the ERPs recorded during IT estimation.

Table 7.8

Correlations between ERP rise times and amplitudes for N1 and P2 deflections from IT ERPs for 62 subjects[a] *at three electrode sites*

IT estimation	O1	O2	Cz
N1	.11	.18	.31 *
P2	.37 **	.28 *	.08

[a] The *N* varies slightly because in some cases a deflection could not be identified. The minimum *N* is 58.

* $p < .05$, ** $p < .01$

The data show that rise times and amplitudes are not independent. To control for the effects of amplitude on rise time, partial correlations (controlling for amplitude) are reported when testing hypotheses. The corresponding zero-order correlations are reported in Appendix V.

7.3.2 Results and discussion on hypotheses

Hypothesis 1[40]

1. IT is inversely related to tests of Gs and Gv. It is predicted that IT will not correlate with tests of Gf or Gc.

Table 7.9 shows the correlations between IT and the WJ-R scores. The prediction that IT would correlate with tests of Gv and Gs but would not share significant variance with tests

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[40] The material relevant to Hypothesis 1 has been submitted for publication as Burns, N.R., Nettelbeck, T. & Cooper, C.J. (1998). *Inspection time correlates with general speed of processing but not with fluid ability.*

of Gf or Gc was partially supported. The only significant correlation between IT and tests from the WJ-R was with Cross Out, a test for Gs.

Table 7.9

Correlations between IT and WJ-R test scores (N = 64)

WJ-R test	IT	
Memory for sentences (Gsm)	–.14	
Cross out (Gs)	–.42	***
Visual closure (Gv)	–.00	
Picture vocabulary (Gc)	–.05	
Analysis-synthesis (Gf)	–.18	

*** $p < .001$ (one-tailed)

This outcome was confirmed by testing the extent to which correlations between IT and the WJ-R tests depends on the intercorrelations of those tests—especially Cross Out and Analysis-Synthesis (see Table 7.2). Table 7.10 shows the partial correlations between IT and the WJ-R tests, with the shared variance with those two psychometric tests controlled. The low correlation between IT and Analysis-Synthesis depends on the shared variance between Cross Out and Analysis-Synthesis, whereas the highly significant correlation between IT and Cross Out is scarcely influenced by partialling Analysis-Synthesis.

A factor analysis of the WJ-R tests using maximum-likelihood extraction described an acceptable one-factor solution ($\chi^2 = 8.4786$, df = 5, $p = .13$). This factor accounted for 33 per cent of the variance of the WJ-R tests and can be interpreted as a higher-order general factor. That is, the five tests chosen from the WJ-R can each be taken to represent a broad second-order ability and the general factor can therefore be viewed as analogous to Carroll's third-order general factor. The correlation between IT and factor scores on this general factor was –.27 ($p < .05$).

Table 7.10

Matrix of partial correlations (controlling for Cross Out and Analysis-Synthesis) of IT estimate and WJ-R tests

	Zero-order	Controlling CO	Controlling AS
MS	–0.14	0.04	–0.08
CO	–0.42***	—	–0.38**
VC	–0.00	0.09	0.04
PV	–0.05	0.08	0.02
AS	–0.18	0.00	—

Note. MS = Memory for Sentences; CO = Cross Out; VC = Visual Closure; PV = Picture Vocabulary; AS = Analysis-Synthesis

**$p < .01$; ***$p < .001$

The results were consistent with hypotheses based on empirical and theoretical considerations (as discussed in Chapter 5). IT correlated with a test of processing speed but not with tests of fluid or crystallised ability. It had been predicted that IT would also correlate with a test of visual processing ability but this prediction was not supported. IT showed a small but statistically significant correlation with a general factor which accounted for 33 per cent of variance of the WJ-R test scores.

These results contribute to an understanding of the reliable correlation previously established between of IT and IQ but within the framework of Gf–Gc theory which is largely consistent with Carroll's three-stratum theory (Carroll, 1993). While the data cannot be seen as definitive, they suggest that IT does not share variance with fluid ability (Gf). Instead, the loading of IT on a general factor depends on the fact that IT shares variance with tests of speed of processing (Gs). These tests are usually defined by the fact that they involve tasks of trivial difficulty such that, given enough time, they can be easily completed without error. Consideration of the backward masking procedure used to define IT suggests that the IT measure shares something of this characteristic.

The lack of correlation between IT and Gv is surprising given the usual correlation of IT with PIQ, which recent analyses have found to measure Gv, in part (Carroll, 1993; McGrew, 1997). It may be that the test of Gv here (Visual Closure) taps an aspect of Gv not important for IT performance. Moreover, in so far as it is well established that IT cannot be rendered completely immune to the contamination of performance by the use of subtle visual cues, including the detection of apparent movement (see Burns, Nettelbeck & White, 1998), it is plausible that IT should reflect something of Gv. However, this issue can only be resolved by a study that includes multiple tests for each of the broad second-order abilities described in hierarchical models of cognitive abilities.

The finding here is consistent with the recent report by Crawford, Deary, Allan and Gustafsson (in press) who administered the WAIS-R to 134 adults. Confirmatory factor analyses supported models suggesting that IT was related to a factor designated 'perceptual organisation' (defined by tests from the PIQ scale excepting the Digit Span test) and only loaded weakly on a general factor (orthogonal to the perceptual organisation factor). That is, as with the findings of Crawford et al., the results here are not consistent with the proposition that general intelligence depends on speed of processing (and specifically on speed of perceptual intake as arguably indexed by IT; see Brand, 1996). Rather, they are appropriately interpreted within the framework of a hierarchical model of cognitive ability that incorporates speed of processing as one element of the model that has equal standing with fluid ability, crystallised ability (see e.g, Stankov & Roberts, 1997). As proposed by Carroll (1993), all of these elements may combine to define a third-order general factor. Including IT in an experimental design that incorporates several tests of each Gf–Gc construct along with other laboratory-based tasks of processing speed will further elucidate the relationships of IT with cognitive ability. This point is discussed further in the general discussion at the end of this chapter.

Hypothesis 2

2(i). Rise times of the early deflections in ERPs recorded from occipital derivations for chequerboard pattern reversal ERPs and for ERPs recorded during IT estimation correlate positively with IT.

Considering first the pattern reversal ERPs, the partial correlation[41] (controlling for N70 amplitude) between N70 rise time and IT was .29 (df = 58, $p < .05$, one-tailed); the partial correlation (controlling for P100 amplitude) between P100 rise time and IT was –.03 (df = 61, ns). The result from the N70 deflection therefore provides support for the hypothesis.

Because the rise time of the P1 could not be reliably measured in the IT estimation ERP, this hypothesis was tested on the N1 deflection from these ERPs. At site O1 the partial correlation was .07 (df = 56, ns); at site O2 the partial correlation was .03 (df = 55, ns). Clearly, these data do not allow rejection of the null hypothesis.

To the extent that the rise times of the first representation of stimulus input at the cortex are immune from re-entrant input (see the discussion in Chapter 6), then the test of this hypothesis via the IT estimation ERPs is deficient because the rise time of the P1 could not be measured and the hypothesis was tested using the longer latency N1 deflection. The same argument holds that, for the pattern reversal ERP, the N70 is likely to provide a better test.

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[41] Appendix V provides tables showing the corresponding raw correlations for all partial correlations presented in this chapter.

However, the partial correlation of .29 between the N70 deflection and IT, while statistically significant, was not as high as expected. Further interpretation on this outcome is deferred until results for subsequent hypotheses have been presented.

2(ii). The rise times measures [as described in 2(i)] correlate negatively with scores on WJ-R. Specifically, these ERP measures will show correlations with tests for Gs, Gsm and Gv rather than with tests for Gf and Gc.

Table 7.11 shows the partial correlations between the rise time measures of N70 and P100 from pattern reversal ERPs, and rise time of N1 from IT estimation ERPs with WJ-R scores.

The same comment as made on the test of 2(i) applies to the outcome of 2(ii). If the results for N70 from pattern reversal ERPs are considered to be the best test of the hypothesis, then the hypothesis was supported to the extent that there was a significant negative correlation between the rise time measure and Cross Out (Gs). Without over-interpreting the outcome, this is consistent with the point made in Chapter 6 that the rise time measure of the ERP can be considered a direct measure of sensory detector capabilities. As such, it should correlate most highly with tests of processing speed and perhaps short-term memory, which are at a lower level of the information processing hierarchy that underlies the model of cognitive abilities described by Gf–Gc theory. Again, further discussion will be deferred until results for subsequent hypotheses have been presented.

Table 7.11

Matrix of partial correlations (controlling for amplitude) between rise time measures from pattern reversal ERP and IT estimation ERP and WJ-R test scores

	MS	CO	VC	PV	AS
Pattern reversal ERP					
N70	–.01	–.28 *	.11	.23	.04
P100	–.03	–.04	.04	.00	–.05
IT estimation ERP					
N1 at site O1	.08	.02	.12	.06	–.02
N1 at site O2	.08	.02	–.11	–.13	–.05

Note. MS = Memory for Sentences; CO = Cross Out; VC = Visual Closure; PV = Picture Vocabulary; AS = Analysis-Synthesis

*$p < .05$, one-tailed

Hypothesis 3

3(i). The rise time measures will be positively correlated with ERP latency. (This means they will therefore be negatively correlated with NCV [as defined by Reed and Jensen]).

This hypothesis was tested against the measures derived from the pattern reversal ERPs. The reason for this was that the NCV measures described by Reed and Jensen were derived from these ERPs. It is not clear that the flash stimulus ERP from IT estimation would have the same characteristics in terms of estimating an NCV as the pattern reversal ERPs (particularly given the effect of stimulus properties on the retinal transduction stage which was assumed by Reed and Jensen to be a constant).

Table 7.12 shows the partial correlations (controlling for the relevant ERP deflection amplitude) between the rise time measures, the latencies, and the NCV derived from the latencies for N70 and P100 from pattern reversal ERPs.

Table 7.12

Matrix of partial correlations between rise time measures and deflection latencies and NCVs calculated from pattern reversal ERPs

	Latency[a]		NCV[a]	
N70 rise time	.30	**	–.28	*
P100 rise time	.33	**	–.30	**

[a] The correlations are for the respective deflections. That is, the N70 deflection rise time correlations are for the N70 deflection latencies and the NCVs calculated from them.

* $p < .05$; ** $p < .01$; one-tailed

Given that the rise time of an ERP deflection constitutes part of the overall latency of the deflection (i.e., the correlation is a part-whole one), then the outcome for this hypothesis, in terms of the directions of the correlations, could be seen as trivial. Nonetheless, the rise time measures account for only about 10 per cent of variance in the latency and NCV measures and, for reasons presented here in Chapter 6, it may be that the rise time measures may capture processes more likely to be critical in determining brain efficiency than just pure axonal conduction of action potentials. (Recall that it was with the latter that Reed and Jensen were most concerned). The merit of this argument will be determined by tests of Hypothesis 3(ii).

For the N70 deflection, the correlation between latency and NCV is –.91 ($p < .001$); for the P100 deflection the corresponding correlation is –.87 ($p < .001$). The correlation between N70 latency and P100 latency is .81 ($p < .001$); the corresponding correlation between the NCVs is .85 ($p < .001$). These correlations support the discussion in Chapter 6 that argued that there are good reasons for believing that the definition of NCV as ERP deflection latency divided by headlength fails to account for the complexities arising from anatomical, functional and methodological considerations. Essentially, the NCV measure contributes no understanding over and above that contributed by a conventional latency measure. Given the outcome shown in Table 7.12, and the very high correlations between the respective NCVs and latencies, then conventional latency measures will be adopted for testing subsequent hypotheses.

3(ii). The ERP latencies recorded at occipital sites will be positively correlated with IT. These latencies will be negatively correlated with tests from the WJ-R measuring Gs, Gsm and Gv rather than with tests for Gf and Gc.

Table 7.13 shows correlations between the N70 and P100 deflection latencies from pattern reversal ERPs and IT and WJ-R scores. Table 7.14 shows the same correlations for the P1 and N1 deflections from occipitally recorded IT estimation ERPs.

Table 7.13

Correlations between latencies of N70 and P100 from pattern reversal ERPs and IT and WJ-R scores

	N70		P100	
IT	.21	*	.18	
Memory for sentences (Gsm)	–.11		–.13	
Cross out (Gs)	–.20	*	–.21	*
Visual closure (Gv)	.02		.05	
Picture vocabulary (Gc)	–.04		–.00	
Analysis-synthesis (Gf)	–.02		–.04	

* $p < .05$ (one-tailed)

Table 7.14

Correlations between latencies of P1 and N1 from IT estimation ERP and IT and WJ-R scores

	P1 latency				N1 latency			
	O1		O2		O1		O2	
IT	.25	*	.17		.25	*	.18	
Memory for sentences (Gsm)	–.32	**	–.31	**	–.20		–.20	
Cross out (Gs)	–.23	*	–.29	*	–.19		–.26	*
Visual closure (Gv)	–.04		–.14		–.11		–.19	
Picture vocabulary (Gc)	–.20		–.16		–.22	*	–.24	*
Analysis-synthesis (Gf)	–.30	**	–.34	**	–.28	*	–.32	**

* $p < .05$; ** $p < .01$ (one-tailed)

Examining the correlations from pattern reversal ERPs, it will be seen that the hypotheses were not supported by the data. IT and N70 latency were significantly correlated. However, the only WJ-R test showing significant correlations with the corrected latency measures was Cross Out (Gs). This is the same outcome as found for the N70 rise time measure but the correlations were not as high as those found for the rise time measure. In other words, it appears that the correlations of N70 latency with IT and Cross Out largely depend on the rise time of the deflection. This was confirmed by subtracting the rise time from the overall latency of the deflection (the remaining portion of the overall latency can be seen as mainly representing retinal transduction time and axonal conduction time) and examining the correlation of the remaining portion of the response with Cross Out and IT. These correlations were near zero and not significant. This finding then provides support for the rise time hypothesis.

Turning to the IT estimation ERPs, in examining the correlations for the P1 deflection it will be seen that the hypothesis was, to a great extent, supported. The predicted relationships of P1 latency with IT and tests of Gsm and Gs were found. The test of Gv showed no significant relationship with P1 latency. However, P1 also correlated with a test of Gf at about .3 ($p < .01$, one-tailed). As noted above, it was not possible to measure P1 rise time for these ERPs and therefore it is impossible to say whether these relationships depend on the rise time portion of the overall latency of the deflection. The pattern of relationships for N1 were similar to those for P1. It should be noted that no such relationships were found for N1 rise time. This outcome runs counter to the argument that these latency correlations with IT and WJ-R scores depend on the rise time of the deflections. However, it becomes difficult to disentangle the various relationships of latency and rise time with IT and cognitive ability scores for ERP deflections past the initial deflection (which is taken to reflect the earliest response of visual cortex).

Hypotheses 2 and 3 were concerned with early ERP deflections—specifically, the N70 and P100 from the pattern reversal ERP and P1 and N1 from the IT estimation ERPs. Overall, the results have been consistent with an information processing hierarchy as depicted in Gf–Gc theory wherein sensory receptor capabilities are at the foot of the hierarchy. The rise times and latencies of the occipitally recorded, short-latency VERP deflections were proposed as indices of the sensory reception stage. The correlations of these rise time and latency measures from both pattern reversal ERPs and IT estimation ERPs with IT, and with measures of Gsm and Gs, follow logically from this proposal (given that IT, Gsm and Gs are at intermediate levels of the hierarchy). However, it should be noted that the pattern of correlations for the two ERP types was somewhat different in that the pattern reversal ERP measures did not significantly correlate with the measure of Gsm whereas those from the IT estimation ERP did. The finding of correlations of about .3 between the deflections from IT estimation ERP with a measure of Gf was not expected. Nevertheless, it is an interesting finding. It can be interpreted as indicating that what are, presumably, higher functions (i.e., relation eduction) share variance with measures of the sensory reception stage. However, these results do not offer any insight into the mechanisms underlying the relationships between the various levels of the hierarchy or between the various levels of measurement that are involved (i.e., physiological measures from the ERPs, a threshold measure of psychophysical performance [IT], and the operationalisation and measurement of psychological constructs such as general processing speed and fluid ability). This point will be elaborated on in the general discussion on the thesis, which constitutes Chapter 8.

The final hypothesis was mainly concerned with the P2 deflection recorded at occipital sites and the N1 and P2 from ERPs recorded from site Cz.

Hypothesis 4

4(i). The P200 rise times will be positively correlated with IT and negatively correlated with WJ-R scores (as described in Hypotheses 2 and 3).

Table 7.15 shows the partial correlations (controlling for deflection amplitude) between the rise times of P2 deflections and IT and WJ-R scores.

Table 7.15

Partial correlations (controlling for amplitude) between P2 rise times from three electrodes and IT and WJ-R scores

	IT	MS	CO	VC	PV		AS
O1 P2	–.01	.09	.06	.04	.21		.14
O2 P2	.02	.05	.12	.31	.14		.17
Cz P2	–.05	.04	–.15	–.17	–.28	*	–.18

* $p < .05$, one-tailed

The table shows that Hypothesis 4 (i) was not supported. Only one correlation from 28 was significant and that correlation could therefore be reasonably regarded as a Type I error. In this sample then, the rise time of the P2 deflections at occipital sites and at Cz are not correlated with IT or with measures of cognitive ability. Discussion of this outcome will be deferred until after subsequent results on Hypotheses of 4 (ii) and 4(iii) have been presented.

4 (ii). P2 latency will be positively correlated with IT and negatively correlated with WJ-R scores (as described in Hypotheses 2 and 3).

Table 7.16 shows the correlations between P2 latencies from IT estimation ERPs and IT and WJ-R scores. Examination of Table 7.16 shows that this hypothesis was not supported. The hypothesis, like the earlier hypotheses, had made predictions about measures of ability below the level of relation eduction. That is, even though the broad abilities described by Gf–Gc theory are given equal weight in the taxonomy of human cognitive abilities, the hierarchy implied by the model recognises differences in the order of the complexity of information processing required for each ability. The approach here has been that IT and the measures derived from ERPs should most strongly correlate with measures of Gsm, Gs and Gv which are at intermediate levels of the information processing hierarchy. While this approach has generally been supported by the findings presented thus far, this is not the case for the data presented in Table 7.16. Further discussion on these findings will be deferred until after the results of 4 (iii) have been presented.

Table 7.16

Correlations between P2 latencies from IT estimation ERPs and IT and WJ-R scores

	IT	MS	CO	VC	PV	AS
O1	.27*	–.10	–.10	–.07	–.01	–.14
O2	.15	–.14	–.13	–.10	–.13	–.18
Cz	.03	–.21	–.19	–.23*	–.44***	–.54***

Note. MS = Memory for Sentences; CO = Cross Out; VC = Visual Closure; PV = Picture Vocabulary; AS = Analysis-Synthesis

* $p < .05$; *** $p < .001$, one-tailed

4 (iii). Rise times and latencies of earlier deflections recorded at non-occipital sites will be positively correlated with IT and negatively correlated with WJ-R scores (as described in Hypotheses 2 and 3).

Table 7.17 shows the correlations between P2 latencies and N1 rise times and latencies from IT estimation ERPs, and IT and WJ-R scores.

Table 7.17

Correlations between P1 latency and N1 rise time and latency from site Cz with IT and WJ-R scores

Site Cz	IT	MS	CO	VC	PV	AS
P1 latency	.13	–.08	–.14	–.14	–.19	–.19
N1 rise time	–.09	–.19	.13	.02	–.01	–.21
N1 latency	.02	–.27*	–.06	–.08	–.21	–.41***

Note. MS = Memory for Sentences; CO = Cross Out; VC = Visual Closure; PV = Picture Vocabulary; AS = Analysis-Synthesis

* $p < .05$; *** $p < .001$, one-tailed

Table 7.16 shows that, apart from a statistically significant correlation at O1 with IT, the only significant correlations between P2 latencies and any of the IT or WJ-R measures were between the latency at site Cz and measures of Gv, Gf and Gc. The P2 deflection, measured at the non-occipital site employed in this experiment (Cz), is correlated most highly with the measures of relation eduction and crystallised ability (which are at the highest level of the information processing hierarchy described by Gf–Gc theory). Further, these findings are supported, to an extent, by the statistically significant correlation between N1 latency and Analysis-Synthesis. In addition, the latency of N1 from Cz correlates significantly with Analysis-synthesis and Memory for Sentences (Gsm). These are interesting findings because, in a sense, they transcend the model proposed here. The aim of the development of the model presented in Chapter 6 and tested in the current chapter was to tie the relationships between ERP deflections and measures of IT and IQ to some understanding of brain function as it may relate to the origin of individual differences in those measures. To do this, it was seen as necessary to focus on the earliest deflections of ERPs because these could be taken to represent the initial response of the cortex to afferent input. The data presented in the discussion of Hypotheses 2 and 3 were consistent with this model. The data in Tables 7.16 and Table 7.17 show that later deflections recorded at a site that is not clearly associated with, say, primary visual cortex, show correlations not with IT or Gs but predominantly with measures of Gf and Gc.

It is also clear that these findings are consistent with the earlier reports of correlations between the P2 deflection and measures of IQ (e.g., Zhang et al., 1989b). What these findings go some way to clarifying is that the relationship between this longer latency deflection and IQ (as measured by omnibus tests) depends on relationships with both fluid and crystallised ability and not with the measures of general processing speed and short-term memory. Indeed, those latter constructs were seen to be related to the earlier deflections of the ERP. It may be that the results here show that the earlier deflections of the ERP are more closely related to the lower levels of the information processing hierarchy and that the later deflections are more closely related to the higher levels of that hierarchy. However, the finding that P1 and N2 (recorded at occipital sites) from the IT estimation ERP were correlated with the measure of Gf does not fit neatly with such an interpretation. Nonetheless, even that finding serves to tie the measures at the physiological level to the psychological measures represented by the WJ-R tests.

The discussion that follows attempts to integrate the results presented in the previous sections.

7.4 General Discussion

The model described in Chapter 6, wherein it was postulated that the rise times of short latency VERP deflections (recorded at occipital sites) index the time taken for the recruitment to firing of neuronal populations in response to afferent input (i.e., what was termed recruitment time), was developed with the aim of providing an account, at the level of a basic property of brain function, that could explain the previously reported relationships between ERP rise times and IT and IQ (these were discussed in Chapter 5). The test of the model described in the current chapter was based in part on an experimental procedure described by Reed and Jensen (1992). The conceptualisation (by Reed & Jensen) of the latencies of N70 and P100 from occipital pattern reversal ERPs as providing estimates of "NCV" within the visual pathway from retina to primary visual cortex was rejected in favour of interpreting the latencies as representing several stages of physiological processing (including, at least, the summation of the time taken for retinal transduction, axonal conduction of action potentials and neuronal recruitment).

A novel aspect of the experiment reported in the current chapter was the operationalisation of cognitive abilities in terms of Gf–Gc theory and the exploration of relationships between the constructs described in that theory and IT, on the one hand, and the measures derived from ERPs (both pattern reversal ERPs and IT estimation ERPs), on the other hand. Specific predictions were made concerning the relationship of IT to the constructs from Gf–Gc theory; directional hypotheses on the relationships of ERP measures and cognitive abilities measures arose from consideration of the information processing hierarchy that underpins the description of cognitive abilities contained in Gf–Gc theory.

The first finding of note was that IT did not correlate with a test of fluid ability. IT only shared variance with a test of speed of general processing. Roberts and Stankov (1997) have proposed that the construct of Gs may be defined by a hierarchy similar to those proposed by Carroll (1993) as defining each of the three strata described in his taxonomy of cognitive abilities. While Roberts and Stankov did not include any visual discrimination tests that used pattern backward masking in their battery, it seems reasonable to suppose that such tests, of which IT may be seen to be a special case (in that it cannot be rendered completely immune to the contamination of performance by the use of subtle visual cues, including the detection of apparent movement), would define a lower-order factor within the hierarchy of abilities that define Gs. Results from Deary's laboratory (e.g., Deary, McCrimmon & Bradshaw, in press) are consistent with this position. As noted earlier, a full test of a proposal which locates performance on pattern backward masking tasks within a hierarchy of abilities that together define a broad general speediness ability would require a sample of at least 100 subjects. The protocol would consist of at least three tests to define each broad second-order ability of interest as well as the administration of several pattern backward masking tasks and perhaps other laboratory based tests of speed (e.g., choice RT tasks) to define the proposed hierarchy of abilities below Gs.[42]

The interpretation of those aspects of the experiment that were concerned with ERP measures is not clear-cut; such has often been the case in the literature on the relationship of ERP measures with measures of cognitive ability (see Deary & Caryl, 1993, 1997). Nevertheless, this aspect of the experiment provided some interesting outcomes, even though it must be admitted that the results of the test of the rise time model were not strong enough to be unequivocally interpreted as supporting that model.

The proposition that the *rise time* of a *short latency* ERP deflection was critical in determining the correlation of the *latency* of that deflection with either IT or a measure of cognitive ability was supported by the finding that the rise time of the N70 from pattern reversal ERP correlated with IT and a measure of Gs. The latency of the N70 deflection also showed the same correlations but when the rise time was subtracted from the latency it was found that for the remaining (i.e., non rise time) period of the overall latency the correlations with IT and the Gs measure were near-zero.

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[42] Such an experiment is currently being planned by the author in collaboration with Drs. Nettelbeck and Cooper.

It was not possible, however, to measure the rise time of the P1 from the IT estimation ERPs and therefore the hypotheses were tested against the subsequent N wave (referred to here as N1 and which had a latency of about 190 ms at the occipital sites). Clearly, this is a deficiency in the experiment that arose for several reasons: first, the flash stimulus employed (i.e., the warning cue from the IT estimation ERP) was of low intensity and therefore the ERPs were of relatively low amplitude. Second, flash ERPs show more intersubject variation than do pattern reversal ERPs (Allison, 1984; this is of course the reason that pattern reversal ERPs are preferred for clinical applications), thereby rendering identification of the P1 more difficult. Third, the hardware configuration in the laboratory was operating at its limits and for some subjects noisy ERPs were recorded, thereby compounding the effect of the first two factors.

The rise times of the early deflections recorded at occipital sites provided no other correlations of interest. However, predictions were made concerning the latencies of these deflections. Significant correlations of the latencies of deflections from both the pattern reversal ERPs and the IT estimation ERPs were found with IT and tests for Gs and Gsm. Additionally, significant correlations of P1 and N1 latencies (from the IT estimation ERP) were found with a test of Gf. The findings from the pattern reversal ERP were consistent with the correlations reported by Reed and Jensen (1992). Of the research on ERPs and IT discussed in Chapter 5, most was concerned with P200, or P300, or both and typically dealt with ERPs recorded from site Cz or other non-occipital sites. Therefore the finding here is the first to report correlations between these early deflections and IT and cognitive abilities. A suggested interpretation of these findings is that the overall efficiency of the earliest processing of visual information relies on some process(es) that is also important for the development of general processing speed and is implicated in efficient retrieval of information from short-term storage. Although the evidence presented here is not definitive, neuronal recruitment is suggested as one candidate process. The correlations with the test of Gf suggest that the same processes are also related to more abstract cognitive processing.

Unlike previously reported research, the P2 deflection rise times did not correlate with IT or the cognitive abilities tests. However, the latency of P2 recorded at site Cz showed the highest correlations of any found in the current experiment. These significant correlations were with tests of Gf and Gc and, at a lesser magnitude, with Gv (the correlations with tests of Gs and Gsm had associated probabilities of .07 and .06, one-tailed, respectively). Additionally, the latency of the N1 deflection from Cz was significantly correlated with the test of Gf. Zhang (1987; Zhang et al, 1989b) found no significant correlations between P200 latency and the IQ test he used but he did report a significant correlation between P200 latency and IT. Caryl (1994) reported correlations between P200 latency and IT of –.3 but correlations with IQ were near-zero. As noted earlier, a subsequent reanalysis of these data (Caryl et al., 1995) identified the epoch 100 to 200 ms post-stimulus as important in correlations with IT and IQ. The experiment reported here had a larger sample than any of those mentioned above. The outcome of the experiment therefore provides strong confirmation of the importance of the P200 deflection as recorded at site Cz as a correlate of cognitive abilities; additionally the latencies prior to P200 were also shown to be important. The highest correlations were those with tests of Gf and Gc, which are at the highest level of the information processing hierarchy.

The arguments in Chapters 5 and 6 pointed to the difficulty of interpreting these types of correlations in terms of brain processes that may relate meaningfully to the psychological constructs under discussion. The suggestion is made here that a VERP deflection with a latency of around 200 ms and recorded at site Cz indexes general brain processes important for all cognitive abilities. Specifically, it is suggested that it is oscillations within the neuronal networks that are involved in processing visual information (i.e., the IT stimuli) that are being indexed by N1 and P2 recorded at Cz. The longer latencies involved arise because the ERP deflections reflect the re-entrant processes occurring as neuronal activation spreads through the networks involved in processing the information. The finding that P2 at Cz may relate to all of the cognitive abilities tested in this experiment (if the near significant correlations from Table 7.16 are counted as Type II errors) points to the generality of the process indexed at these latencies.

The suggestion that the early, occipitally recorded deflections are related to the intermediate levels of the hierarchy of information processing, and that the later deflections recorded at Cz are related to the higher levels of the information processing hierarchy, has appeal because of its symmetry. However, the data are not entirely congruent with this suggestion. Rather, the data suggest that the ERP measures follow the suggested pattern but that the early deflections also correlate with, for example, Gf; and conversely the later deflections also show some relationship with Gs and Gsm. The foregoing highlights the advantage of using a finer grained approach to the description of cognitive abilities. Previous research has been limited to speculation about relationships with omnibus IQ measures or at best poorly defined constructs such as PIQ and VIQ from the Wechsler scales. Possible directions for future research in this area and based on this approach will be discussed in the final chapter of the thesis.

In summary, this chapter has found: that IT is not related to fluid ability; that the rise times of early VERP deflections recorded at occipital sites are important in determining correlations of those deflections with IT and with cognitive abilities; that the latencies of the early VERP deflections recorded at occipital sites correlate with measures assumed to be at the intermediate level of a hierarchy of information processing, that is, IT, general processing speed and short-term memory. Correlations were also found with fluid ability; the latency of

P2 recorded at site Cz correlated most strongly with fluid and crystallised ability but appeared also to be related to the other measures of cognitive ability tested in this experiment.

The final chapter will discuss all of the work presented in the thesis. Possible implications of the findings presented in this thesis, for research that seeks to understand cognitive abilities via their relationships with physiological and psychophysical measures, will be addressed. Some suggestions for future research programs will be made and discussed in the context of the findings presented here.

Chapter Eight: General Discussion

8.1 The nature of IT

As noted in Chapter 1, this author's theory about the nature of IT differs from that taken by the originators of the measure at the time that they developed the measure. This is because recent theorising and research (Burns, Nettelbeck & White, 1998; White, 1993, 1996) has led to a conceptualisation of IT as an idiosyncratic pattern backward masking task. The nature of the idiosyncrasies of IT are at least two-fold (Burns, Nettelbeck & White, 1998; White, 1996): (i) the configuration of the target and mask is such that the possibility of the perception of apparent movement is high because, as the mask replaces the target, two possible sources of apparent movement are generated. First, vertical apparent movement, which occurs on both sides of the target figure (the lines 'grow longer') and, second, horizontal movement, seen as movement away from the side of the figure with the longer line (refer to Figure A3.2 as an aid to following these descriptions); and (ii) the estimation of IT threshold at very high levels of accuracy (in this thesis the 90% level was used) may render the estimates somewhat unstable (Levy, 1992. To address this possibility, in this thesis two estimates were obtained in the experiments reported, and the means of these estimates were used for further analyses). This second idiosyncrasy is a methodological issue that may readily be resolved by adopting the practice of estimating threshold at a level halfway between chance level and perfect performance (i.e., 75% correct in the case of IT) and it will not be considered further. However, the first issue (i.e., the apparent movement which arises as the target is replaced by the mask) has interesting implications for the relationships of IT with cognitive abilities. These implications are as follows: (i) if the detection of apparent movement is a process that needs to be learnt over an extended period of performance on the task; or, if it is a phenomenon that only operates for a few individuals; or, if it does not matter whether subjects use the available apparent movement, then, it is probably irrelevant to the relationship of IT with cognitive abilities and, therefore, the same relationship with cognitive abilities should be found for all pattern backward masking tasks (and other visual processing tasks of limited complexity—e.g., Deary et al., 1998); but (ii) if the IT–cognitive abilities relationship depends on the detection of apparent movement in the task, then the relationship will be specific to the IT task (and perhaps other tasks dependent on the detection of apparent movement or other subtle visual cues).

It seems likely (see Burns, Nettelbeck & White, 1998) that the IT–cognitive abilities relationship will generalise to other pattern backward masking tasks. Further, as outlined in Chapter 7, and following Roberts and Stankov (1998), it is predicted that performance on such tasks would define a lower-order factor of performance on pattern backward masking tasks within a hierarchy that itself defines broad general processing speed (Gs). Evidence for this possibility is provided by the findings described here in Chapter 7, by the findings of Crawford et al. (in press), and recent findings on the nature of PIQ from the Wechsler scales (discussed here in Chapter 5). However, as noted above, because IT cannot be rendered completely immune to the contamination of performance by the use of subtle visual cues, it is also expected that IT reflects something of Gv.

Evidence presented in Chapter 7 on the relationship of IT with tests of constructs from Gf–Gc theory was consistent with the view outlined above. The evidence from ERPs was less supportive of this position but, nevertheless, some of the evidence could plausibly be interpreted within such a framework. For example, the finding that short latency sensory ERP deflections are related to IT and to constructs at intermediate levels of the Gf–Gc information processing hierarchy, is consistent with the preceding discussion.

Analysis of these relationships at this level of description necessitates adopting an operationalisation of cognitive abilities that allows such differentiations to emerge. This point is discussed further in the next section.

8.2 The conceptualisation of cognitive abilities

In a recent article, Deary and Caryl (1998), who are proponents for the reductionist approach to understanding human intelligence (e.g., Deary, 1996), stated that a hierarchical description of human cognitive abilities was "attracting a growing consensus among experts in the field" (p.365). The material reported in Chapter 7 is the first research, of which the current author is aware, that has attempted to understand the relationship of IT with cognitive abilities within such an hierarchical description. When considered along with those aspects of the experiment reported in Chapter 7 that were concerned with ERPs, it seems evident that this approach will prove fruitful. That is, future research should incorporate measures that are operationalisations of the constructs described in Gf–Gc theory; or, they should at least incorporate adequate batteries of tests and use large enough samples so that Carroll's (1993) approach to the factor analysis of cognitive abilities can be followed.[43]

Indeed, Carroll (1993) argues that "neurobiological work be guided by factor-analytic results ... that indicate what kinds of abilities are measured by various tests. The Raven Advanced Progressive Matrices test, for example, measures only one kind of abstract reasoning, and tends to measure spatial abilities as well. To the extent possible, neuropsychological research should attempt to find correlates between physiological phenomena and measures of particular abilities freed of the influence of other abilities" (p.662). The research presented in Chapter 7 was a first step in this direction. A later section of this chapter will sketch an idealised research program that continues in the same direction.

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[43] Carroll's (1993) reanalysis of D.E. Hendrickson's (1982) data, for example, showed that the string measure had its primary loading on his factor 2V (i.e., general visual perception). For reasons explicated in this thesis, the author does not wish to dwell on interpretations of the string measure, nevertheless, the point made on adopting a view of human cognitive abilities that goes beyond assuming that WAIS-R IQ scores are measures of Spearmans's *g* is supported by this finding of Carroll's.

8.3 Inferences on IT derived from relationships with ERPs

Chapter 5 contained a discussion on the argument of Zhang (Zhang et al, 1989a) on the relationship between P200 and IT. Briefly, Zhang argued that the finding that IT was related to P200 was consistent with a finding (Chapman et al., 1978) that P200 covaried with the process of encoding (semantic) information into short-term memory. The consistency in these findings arises because IT was considered by Zhang to be a measure of the speed of encoding visual information. In Chapter 5, the current author pointed to a conceptual problem with Zhang's inference. The problem revolves around the validity of the assumption that the P200 which Zhang recorded was the same as the P200 recorded in Chapman et al.'s procedure. Cacioppo and Tassinary (1990) pointed out that this form of inference violates the logic of hypothetico-deductive research because "inferences in the psychological domain are not based so much on the exclusion of alternative hypotheses as on reasoning by analogy ... a physiological response is identified that is affected by variations in the psychological process of interest. This physiological response is subsequently monitored ... in an effort to determine the likely presence or extent of the psychological process of interest" (p.15). This is not to say that Zhang was wrong but rather that alternative inferences are possible.[44] In other words, the form of the relationships do not allow *strong* inferences (Sarter, Berntson & Cacioppo, 1996).

In Chapter 7, a significant correlation between IT and the rise time of the N70 deflection, from pattern reversal ERPs, was reported; the N70 was also significantly correlated with a test of general processing speed (Gs). Both IT and Gs, as well as a test of short-term memory (Gsm), were significantly correlated with latencies of P1 and N1 from IT estimation ERPs. These findings can be interpreted as supporting Zhang's (Zhang et al.,

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[44] Indeed, Caryl (1994) refined the understanding of the relationship between ERPs and IT by identifying the latency range 100 to 200 ms post stimulus as being important and identified a range of processes, including stimulus identification, resource allocation and attentional influences, that had been shown to covary with ERP parameters in this latency range.

1989a) argument although they do not involve the P200 deflection. That is, the set of correlations (from two different VERP tasks) show that the shorter the ERP latency and rise time (i.e., the faster the response of the brain), the shorter is IT and the higher are the scores on tests of speed and short-term memory. To an extent, these findings represent an advance in the description of the range of interrelationships between the different levels involved (i.e., physiological, psychophysical, psychological). They also provide converging evidence on the proposition that some common processes underlie speed of brain response and some measures of cognitive abilities (including those dependent on short-term memory). However, the nature of which processes are involved is open.

The same problem (i.e., making inferences on the process involved) arises in trying to understand why the latency of P200, recorded at Cz, significantly correlates with measures of fluid and crystallised abilities. This finding is congruent with the literature reviewed in Chapter 5 and so there are now a diverse series of studies pointing to this region of the ERP as being a covariate of higher level cognitive abilities. However, strong inferences on the nature of the causal relationships involved is not possible on the basis of the ERP methodology used in studies conducted thus far. Recent developments in the technology of recording EEG and the analyses of the signals so recorded may advance the possibility of understanding the processes behind what appear to be robust findings on ERP relationships with IT and cognitive abilities. This possibility is described further at the conclusion of this chapter.

Another possible line of enquiry involves establishing whether the manipulation of one of the variables of interest has the expected effect on the other. For instance, do manipulations that affect the latency of early VERP deflections also affect IT? At the level of the physiological characteristics of visual processing, this relationship is easily demonstrated. The contrast of the pattern used in VERP recordings affects the latency of the early deflections; the lower the contrast the longer the latency of the deflection (Chiappa, 1990).

Similarly, Burns, Nettelbeck, White and Willson (in press) demonstrated that decreasing the contrast between the IT target and its background resulted in increased IT estimates. Conversely, does a treatment that may exert more central effects in acting to increase IT also increase N70 rise time or P1 latency? For example, ingestion of alcohol is known to increase CSOAs on backward pattern masking tasks (reviewed by Moskowitz & Robinson, 1988). Does a similar increase in ERP latency follow the ingestion of alcohol? Finally, there is nonexperimental evidence that supports the finding that N70 latency and IT covary: it is well known that both N70 latency and IT increase from about the age of 60 years onward (see Halliday, 1978 on the former, and Nettelbeck, 1987 on the latter). Clearly, there are many avenues left to explore on the relationships between ERPs and IT. Some of these may further understanding of the relationship between IT and cognitive abilities.

8.4 The string measure

Chapter 2 of this thesis presented a comprehensive review of the theoretical bases and empirical research on the Hendrickson string measure (and other measures of ERP complexity). Chapter 3 reported an empirical test of Bates et al.'s (1995) attentional theory on the string measure and discussed some possible reasons for the lack of agreement between the findings reported here and the findings reported by Bates (e.g., Bates & Eysenck, 1993). Chapter 4 presented a new theory on the relationship of the string measure to cognitive abilities. This theory was designed to take account of the biophysics of the EEG and showed how neglect of an understanding at this level of explanation was likely to lead to overambitious theorising on relationships between physiological measures and psychological constructs.

The overall outcome of the literature review, the experimental test, and the test of the new model was summarised in the abstract of Burns et al. (1997): "it was found that the string measure was nonspecific in that it indexes both low and high frequency event-related activity;

the string measure is also dependent on ERP amplitude. The string measure is therefore not a valid measure of the ERP. It was concluded that the string measure should be abandoned" (p.43).

Robinson (1997) appeared within a month of the publication of the Burns et al. (1997) article referred to above. Robinson adopted an entirely different methodology for examining the string measure. He recorded one channel of EEG that was then split, prior to amplification and passage through analogue filters, so as to differentiate between the overall EEG signal, on one hand, and the low (0-14 Hz) and high (14-8000 Hz) frequency activity that constituted the EEG signal, on the other hand. Nevertheless, one of his main findings was that the string measure was mainly related to high frequency activity. The current author disagrees with Robinson's contention that the string measure does not index ERP amplitude (although Robinson restricted his claim to procedures that 'replicate' D.E. Hendrickson's, 1982 procedure). Both the current author and Robinson (1997; Robinson & Behbehani, 1997) are agreed that the string measure is not a useful research tool because it fails to take account of the biophysics involved in the recording of brain activity.[45]

The paper by Bates et al. (1995) assumed that the string measure was valid and presented a theory that string measure correlations with IQ depended on the attentional demands of the experimental procedure employed (see Chapter 3 of this thesis). The current author argues that Bates' result was not conclusive. This argument is supported by Batt, Nettelbeck and Cooper's (1997) recent findings. These authors reported an experiment that included a replication of the Bates et al. procedure but with a larger sample (*N* = 35); they failed to replicate the three-way string measure by IQ by attentional demand interaction

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[45] It is this failure, in the view of the current author, that causes the measure to not be replicable in its relationship with cognitive abilities measures. As has been pointed out to him on numerous occasions, this fact would be irrelevant if the measure consistently correlated at .8 with IQ—but it does not.

reported by Bates et al. Further, Batt (personal communication, November, 1997) has shown that an outcome equivalent to that of Bates et al.'s could be obtained about 5 times in 100 by drawing random samples of 23 subjects from Batt et al.'s (1997) data on 35 subjects. That is, it is possible that the Bates et al. result arises as Type I error.

Given such an outcome, it is essential that future samples of adequate size be employed in this field of research. Furthermore, because the same point was made in one of the three major reviews that have appeared in the last 15 years (Barrett & Eysenck, 1992, p.281), there appears to be no reason why a sample size of at least 40 should not be required by the editors of journals in the field.[46]

The two reports of high correlation between the string measure and IQ (D.E. Hendrickson, 1982; Stough et al., 1990) have been discussed in Chapter 2, and the current author agrees with Robinson's (1993) conclusions on the likelihood that the correlations of the Hendricksons were inflated and that Stough et al.'s report focussed too much on one or two high correlations rather than assessing the overall pattern of their results. On the other hand, these and several other studies reporting significant correlations between the string measure and IQ (Blinkhorn & Hendrickson, 1982; Gilbert et al., 1990; Haier et al., 1983; Stough, 1994) suggest that it is reasonable to conclude that these measures do share variance. Given that the string measure is a nonspecific index of event-related brain activity, then, under certain unspecifiable conditions, correlations will be found between the string measure and IQ. The current author regards the nonspecificity of the string measure as sufficient reason to abandon the string measure. This is because he argues that the use of ERPs in studies on cognitive abilities implies that an attempt is being made to bridge the gap between the physiological level of description and the psychological level of description. The mere

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[46] A sample of 40 has power of .83 ($\alpha = .05$, one-tailed) to detect an effect size of .5 (i.e., the order of correlation found between IT and Gs in Chapter 7 of this thesis).

reportage of the odd high correlation between a measure derived from the EEG and a measure of cognitive ability is, basically, nothing more than a statement that the brain and intelligence have something to do with each other (see also Detterman, 1994).

8.5 The rise time model

The rise time model described in Chapter 6 represented an attempt to link neuronal recruitment time, as a facet of brain efficiency, with tests of cognitive ability (described as an information processing hierarchy). The model proposed that rise times of short latency VERP deflections reflect neuronal recruitment time and that efficiency of neuronal recruitment may, in part, underlie the efficiency of neural processing of information. It was argued that such a model would account for the previously reported relationships of ERP rise time measures with IQ scores and with IT. The outcome of the test of this model was that, although rise time of N70 from pattern reversal ERPs did correlate with a test of Gs and with IT, the predictions from the model were not met. For reasons discussed in Chapter 1 of this thesis, the possibility of Type II error is the constant companion of researchers on cognitive abilities who choose to use ERPs to investigate individual differences. However, the finding of much stronger correlations between latencies of ERP deflections with cognitive abilities test scores than were found for the rise time measures, suggests that the rise time model failed on its merits. The N70 rise time correlations can be interpreted as indicating that efficiency (or speed) of whatever process[47] is indexed by the rise time of these ERP deflections may be important for fast information processing.

The finding that latencies of ERP deflections correlated with IT and with cognitive abilities was unexpected. This was because, as Deary & Caryl (1993) had noted, even though

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[47] If the predictions of the rise time model had been met, a next step in the research program would involve testing the assumption that ERP rise times reflect neuronal recruitment. Such a test would involve intracortical recording, presumably in other species. At this stage there is no justification for undertaking such a test.

such a finding is a straightforward prediction from a speed of processing hypothesis about individual differences in cognitive abilities, no consistent pattern is found in the literature. It may be, given the suggestions made on the basis of the outcome of the experiment reported in Chapter 7, that if psychometric tests are used that measure broad second-order abilities (as opposed to using omnibus tests of IQ), and careful attention is paid to response topography in relation to what is known about brain structure, then ERP latency will prove a more reliable correlate of cognitive abilities than has hitherto been the case. Further discussion on this point will be found in the next sections.

8.6 Prospects

8.6.1 Inspection time

In Chapter 7, and in the current chapter, the likelihood that IT would be one of a number of pattern backward masking tasks that define a lower-order factor subordinate to a broad general speed of processing factor, within the structure of human cognitive abilities, was discussed. It was also noted that IT, because of the inherent possibility of the detection of apparent movement, as the mask replaces the target, may also share variance with a broad general visualisation ability factor. An experimental protocol, currently in the early stages of execution, that would address these issues was described briefly in Chapter 7 and in Burns, Nettelbeck and Cooper (1998). The outcome of this experiment, it is hoped, will be the resolution of the location of IT within the structure of human cognitive abilities. However, there are other issues on the understanding of IT that remain to be explored. Some of those that may be investigated via ERPs are discussed in the final section of this chapter.

8.6.2 Understanding via ERPs?

There are two issues that will be addressed in this last section and they reflect the issues examined in the thesis—that is, IT and its relationships with cognitive abilities. First, the ERP methodology used in this thesis, and in all other work that has examined ERP relationships with cognitive abilities, will be discussed in the context of recent advances in EEG methodologies (i.e., high resolution EEG recording and sophisticated processing of the resultant data thereby leading to information on important aspects of cognitive processing). It will be argued that there is little point in continuing research in the area under discussion unless the most powerful techniques available are adopted. This is, of course, easy to say in the context of the current discussion and it is acknowledged that the relevant hardware and software is not cheap. But, on the other hand, these new EEG methodologies are far more accessible and tractable than alternative approaches to examining brain function (e.g., positron emission tomography (PET) or functional magnetic resonance imaging (fMRI); see Haier, 1993). Second, the possible application of these methodologies to the issues under consideration will be discussed.

Turning to the first point: at best, research in the area under discussion has been limited to EEG recording systems using the 19 electrode sites that define the '10/20' montage of electrode placement (Jasper, 1958). While, as has been emphasised at several points in this thesis, the ERP offers excellent temporal resolution, spatial resolution is severely limited by the use of a small number of recording electrodes.[48]

Recent advances in EEG recording methodologies have used from 100 up to 256 recording electrodes. These methodologies increase the spatial resolution of the EEG from something in the order of 6 cm (in recordings from adults) to something in the order of 1.5 cm (see e.g., Gevins et al., 1995). In and of itself, this increase in spatial resolution does not offer the possibility of identifying the source of the potentials recorded. However, there are also statistical manipulations that do offer this possibility. Specifically, the use of the Laplacian

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[48] The EEG laboratory in which the research reported in this thesis was conducted was limited to recording from eight channels; on the other hand, there was access to state-of-the art software for processing the recorded signals.

transformation of the electrode voltages (specifically, the second spatial derivative) is thought to be proportional to the current that enters and exits the scalp at each electrode site. Given certain assumptions (see Gevins, Leong, Smith, Le & Du, 1995), these techniques allow that the spatial resolution of the EEG is comparable to that obtained from the much more expensive MRI methodology.

The experiment reported in Appendix III of this thesis is an example of the type of experiment that would provide much valuable information on the processes involved in performance of the IT task, if it had been performed with an EEG montage of 100 or more electrodes. Recall that that experiment was concerned with the comparison of ERP responses to IT stimuli presented at an SOA such that about 75% of trials were correctly discriminated. If high resolution EEG had been used in conjunction with MRI brain scans (or at least strereotaxial mapping of the scalp of the individual subjects), then, a comparison of the difference between correct and incorrect discriminations would have been useful in resolving where differences between correct and incorrect discriminations might lie. Such an experiment would probably resolve the controversy on the question of whether the IT delay arises at the level of the visual cortex (or earlier; White, 1993, 1996) or at more central stages of processing.

In a similar vein, current methodology allows for EEG recording during task performance. Therefore, there is no reason why subjects' EEG could not be monitored as they were actually undertaking psychometric tests. At the least, such an endeavour, while requiring massive computations on the EEG data, would provide far finer detail on individual differences in brain function than has so far been possible (Giannitrapani, 1985, is the model for such an approach). Such an experiment would be far more feasible (practically and economically) than Haier et al.'s (1988) PET studies. In conclusion, the current author would argue that the fact that relationships between ERP deflections at 'isolated' electrode sites and tests of broad cognitive abilities seem to suggest that a meaningful hierarchy of information processing exists, then, the more powerful methodologies available will provide more information than has been provided thus far.

In final summary, the results presented in the second half of this thesis suggest that a research program based on an operationalisation of cognitive abilities as described in Gf–Gc theory, coupled with a conceptualisation of IT as representative of pattern backward masking tasks in general, and the use of high resolution EEG methodologies will resolve the outstanding issues on the relationship of IT with cognitive abilities.

Appendix I: Additional data relevant to Chapter 4

Hypothesis 1. ERP string measure and ERP amplitude measures are positively related.

Table A1.1

Correlations between ERP string measure and P200 and P300 baseline-to-peak amplitude measures from 40 subjects at three electrode sites for three conditions.

P200	Fz		Cz		Pz	
Cue-alone ERP	.47	**	.34	*	.55	**
IT-warning cue ERP	.50	**	.41	**	.37	*
IT-stimulus ERP	.23		.43	**	.10	
P300						
IT-stimulus ERP	.22		.50	**	.49	**

**p* < .05; ***p* < .01, two-tailed

Table A1.2

Correlations between ERP string measure and absolute amplitude measure for 500 ms epoch from 40 subjects at three electrode sites for three conditions.

P200	Fz		Cz		Pz	
Cue-alone ERP	.43	**	.36	*	.58	**
IT-warning cue ERP	.51	**	.52	**	.69	**
IT-stimulus ERP	.28		.52	**	.37	*

**p* < .05; ***p* < .01, two-tailed

Hypothesis 2. The string measure of the ERP indexes event-related power across the full spectrum from low to high frequencies.

Table A1.3

Correlations between ERP string measure and ERP spectral bandpower from 40 subjects at three electrode sites for three conditions.

		Delta	Theta	Alpha	Beta
Fz	Cue-alone ERP	.08	.42**	.57**	.72**
	IT-warning cue ERP	.17	.68**	.75**	.62**
	IT-stimulus ERP	.16	.29	.49**	.59**
Cz	Cue-alone ERP	.03	.43**	.59**	.77**
	IT-warning cue ERP	.20	.52**	.83**	.50**
	IT-stimulus ERP	.36*	.42**	.75**	.68**
Pz	Cue-alone ERP	-.05	.37*	.81**	.79**
	IT-warning cue ERP	-.03	.49**	.98**	.77**
	IT-stimulus ERP	.21	.61**	.80**	.76**

*$p < .05$; **$p < .01$, two-tailed

Table A1.4 shows the intercorrelations of spectral bandpowers. These data were used to assess the effectiveness of the windowing in the Fourier analysis and to assess possible collinearity of the spectral bands prior to the multiple regression procedure.

Collinearity diagnostics from SPSS procedure REGRESSION confirmed that no action was necessary.

Table A1.4

Intercorrelations of spectral bandpower from 40 subjects at three electrode sites for three conditions

		Fz			Cz			Pz		
		Delta	Theta	Alpha	Delta	Theta	Alpha	Delta	Theta	Alpha
Cue-alone ERP	Theta	.42**			.44**			.18		
	Alpha	.08	.36*		.04	.30		-.02	.24	
	Beta	-.03	.01	.01	-.12	.11	.13	.08	.44**	.40*
IT-warning cue ERP	Theta	.45**			.69**			.43**		
	Alpha	-.02	.33*		.00	.23		-.03	.44**	
	Beta	.24	.31*	.20	.02	.09	.16	-.01	.46**	.67**
IT-stimulus ERP	Theta	.08			.37*			.48**		
	Alpha	-.01	-.06		.23	.22		.18	.37*	
	Beta	.38*	-.08	.04	.35	.19	.27	.03	.49**	.45**

**p* < .05; ***p* < .01, two-tailed

Table A1.5

Coefficients of determination (R^2) and change in R^2 for hierarchical multiple regression of ERP spectral bandpower and ERP absolute amplitude onto ERP string measure at three electrode sites for three conditions

	Fz		Cz		Pz	
Cue-alone ERP	R^2	Change in R^2	R^2	Change in R^2	R^2	Change in R^2
1. Delta	.01	.01	.00	.00	.00	.00
2. Theta	.19	.18 **	.21	.21 **	.15	.15 *
3. Alpha	.39	.20 **	.44	.23 **	.69	.54 ***
4. Beta	.89	.50 ***	.89	.45 ***	.92	.22 ***
5.Amplitude	.89	.00	.90	.01	.92	.01
IT-warning cue ERP						
1. Delta	.03	.03	.04	.04	.00	.00
2. Theta	.48	.45 ***	.31	.27 ***	.32	.32 ***
3. Alpha	.77	.28 ***	.80	.49 ***	.96	.64 ***
4. Beta	.91	.14 ***	.93	.13 ***	.98	.02 ***
5.Amplitude	.91	.00	.93	.00	.98	.00
IT-stimulus ERP						
1. Delta	.03	.03	.13	.13 *	.04	.04
2. Theta	.10	.08	.23	.10 *	.38	.34 ***
3. Alpha	.36	.25 **	.64	.41 ***	.77	.39 ***
4. Beta	.71	.35 ***	.85	.21 ***	.87	.11 ***
5.Amplitude	.74	.03	.86	.01	.88	.01

[a] Amplitude is the absolute amplitude measure of the 500 ms epoch

**p* < .05; ***p* < .01; ****p* < .001, two-tailed.

Appendix II: The Woodcock-Johnson Psycho-Educational Battery-Revised

This appendix contains a description of the Woodcock-Johnson Psycho-Educational Battery-Revised (WJ-R; Woodcock & Johnson, 1989) and describes the outcome of the evaluation of this battery for use in the current investigation on the relationship of IT with cognitive abilities.

The WJ-R is two separate batteries. The first battery is the WJ-R Tests of Cognitive Ability, the second battery is the WJ-R Tests of Achievement. The subjects in the standardisation sample for the WJ-R were administered both batteries. Only the WJ-R Tests of Cognitive Ability are considered here and the abbreviation WJ-R, when used hereafter and in the body of the thesis, refers only to the cognitive ability battery.

The WJ-R is an operationalisation of the Horn-Cattell model of fluid and crystallised general abilities (Horn & Cattell, 1966; the model has been recently described by Horn, 1985, 1987, 1988; Horn & Noll, 1994 and is commonly referred to as the Gf–Gc model of cognitive abilities). That model describes a profile of broad second-order abilities defined by their relationship with tests of primary abilities, and with each other. The WJ-R provides tests for seven of those second-order abilities (additionally, tests for an eighth broad ability, general quantitative ability (Gq), are provided in the WJ-R Tests of Achievement). The WJ-R contains a standard battery of seven tests and two supplementary batteries also each containing seven tests. That is, there are three tests for each of the seven second-order factors. However, the second of the supplementary batteries is provided mainly for clinical settings and is not considered further here. To maintain confidentiality of the test material, descriptions of the 14 tests from the standard and the first supplementary battery are taken from Woodcock (1990, pp.235-6) and shown in Table A2.1.

The WJ-R technical manual (McGrew et al., 1990, pp.163-179) presents evidence on the goodness-of-fit of the data from the standardisation sample to the seven factor model based on Gf–Gc theory. Confirmatory factor analysis and exploratory factor analysis (with oblique rotation) both reproduced the hypothesised model well from the standardisation sample data. The former procedure resulted in a Goodness-of Fit Index of .976 (perfect fit = 1). The latter procedure showed that none of the tests loaded at above .3 on any factor other than the factor that the test was hypothesised to measure. Factor loadings of the 14 tests on the 7 factors they were hypothesised to measure ranged from .473 to .903.

Table A2.1

Description of the tests from the standard and supplemental batteries of the WJ-R

Test (Factor symbol)[49]	Description
1. Memory for names (Glr)	Measures the ability to learn associations between unfamiliar auditory and visual stimuli (an auditory-visual association task). The task requires learning the names of a series of space creatures.
2. Memory for Sentences (Gsm)	Measures the ability to remember and repeat simple words, phrases, and sentences presented auditorily by a tape player.
3. Visual Matching (Gs)	Measures the ability to quickly locate and circle the two identical numbers in a row of six numbers. The task proceeds in difficulty from single-digit to triple-digit numbers and has a 3-minute time limit.
4. Incomplete Words (Ga)	An audio tape test that measures auditory closure. After hearing a recorded word that has one or more phoneme missing, the subject names the complete word.
5. Visual Closure (Gv)	Measures the ability to name a drawing or picture that is altered in one of several ways.
6. Picture Vocabulary (Gc)	Measures the ability to name familiar and unfamiliar pictured objects.

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[49] See Table 5.1 in Chapter 5 for a description of the factors and an explanation of the symbols.

Test (Factor symbol)[49]	Description
7. Analysis-Synthesis (Gf)	Measures the ability to analyse the components of an incomplete logic puzzle and to determine the missing components.
8. Visual-Auditory Learning (Glr)	Measures the ability to associate new symbols (rebuses) with familiar words in oral language and to translate a series of symbols presented as a reading passage.
9. Memory for Words (Gsm)	Measures the ability to repeat lists of unrelated words in the correct sequence. The words are presented by audio tape.
10. Cross Out (Gs)	Measures the ability to quickly scan and compare visual information. The subject must mark the five drawings in a row of 20 drawings that are identical to the first drawing in the row. The subject is give a 3-minute limit to complete as many rows of items as possible.
11. Sound Blending (Ga)	Measures the ability to integrate and then say whole words after hearing parts (syllables and/or phonemes) of the word. An audio tape is used to present word parts in their proper order for each item.
12. Picture Recognition (Gv)	Measures the ability to recognise a subset of previously presented pictures within a larger set of pictures.
13. Oral Vocabulary (Gc)	Measures knowledge of word meaning. In Part A: Synonyms, the subject must say a word similar in meaning to the word presented. In Part B: Antonyms, the subject must say a word that is the opposite in meaning to the word presented.
14. Concept Formation (Gf)	Measures the ability to identify and state the rule for a concept about a set of coloured geometric figures when shown instances and non-instances of the concept.

Note. Source: Woodcock (1990, p.235)

According to the criteria used by Woodcock (1990), each of the 14 tests described in Table A2.1 is a *clean* measure of the factor it is hypothesised to measure. By this he means that in the standardisation and concurrent validity samples the tests had either a primary factor loading greater than .5, or else a primary loading less than .5 but with any secondary loading being less than one-half of the primary loading.

Evaluation of the WJ-R for use in this thesis

Initial evaluation of the WJ-R involved determining the time taken to administer the 14 tests from the standard and supplemental batteries, and assessing the appropriateness of the various tests for the population they were to be used with—that is, adult Australians. The full standard battery (tests 1-7, see Table A2.1) was administered to four high ability subjects (i.e., candidates for postgraduate degrees). Two of these subjects also completed the full supplemental battery (tests 8-14, see Table A.2.1).

The time taken to administer the seven tests constituting the standard battery was consistent with the range given in the Examiner's Manual (Woodcock & Mather, 1989). That is, the testing required about 40 minutes. The same length of time was required to administer the seven tests from the supplemental battery.

All four subjects were encouraged to make comments on any aspects of the test they found noteworthy. All four subjects indicated that the test *Incomplete Words* from the standard battery was rendered very difficult by the unfamiliar (i.e., American) accent on the audio tape recording used to administer this test (see Table A2.1). Similar comment was made regarding the test *Sound Blending* from the supplemental battery. Although in the same accent, audio tape presentations of the tests *Memory for Sentences* and *Memory for Words* did not present much difficulty (although one subject said that he found it hard to resist mimicking the accent). The Examiner's Manual (Woodcock & Mather, 1989, p.47) states that *Incomplete Words* cannot be presented by live voice. No such statement is made regarding

Sound Blending, but this author is of the opinion that it would be very difficult, if not impossible to present this test by live voice. The possibility exists of making a new tape in an Australian accent but this would require much care (and no little expense). These two tests both measure Ga–i.e., auditory processing, and it was decided not to use them in this thesis. This decision rested mainly on the fact that, *prima facie*, tests of auditory processing are unlikely to relate closely to measures of visual IT or to measures derived from visual ERPs. Similar considerations justified the exclusion of the tests *Memory for Names* and *Visual-Auditory Learning* from this thesis. This was again because it was considered unlikely that tests of Glr–i.e., long-term retrieval would relate directly to IT or to ERP measures on IT.

Of the remaining tests in the standard and supplemental batteries of the WJ-R, the selection shown below was made for use in this thesis. The decisions were based on several factors: first, it was deemed appropriate to have at least one marker test for each of the remaining five abilities (i.e., Gsm, Gs, Gv, Gc, and Gf). This is because, as described in Chapter 5, one aim of this thesis was to test whether IT is related to Gf, or to Gv and/or Gs. There has also been speculation as to the role of short-term memory in IT and similar tasks a test of Gsm was therefore thought likely to be useful. The question of the relationship of Gf–Gc factors to measures derived from ERPs is also open. Second, because the experimental program required subjects to complete cognitive abilities testing, IT estimation, and ERP recording, the time taken to administer the cognitive abilities tests was a consideration. It was decided to select one marker test for each of the five second-order abilities. Tests were selected from the standard battery except for Cross Out, the test for Gs. This test, from the supplemental battery requires matching shapes rather than numbers and was therefore thought to be more appropriate in the context of an experiment on IT.

The tests used in the investigations reported in Chapter 7, along with the broad ability that each test is a marker for are shown in Table A2.2.

Table A2.2

Tests from the WJ-R used in this thesis and the corresponding factor that each test measures

Test	Factor
Memory for Sentences	Gsm
Cross Out	Gs
Visual Closure	Gv
Picture Vocabulary	Gc
Analysis-Synthesis	Gf

Appendix III: An evaluation of ERPs recorded at IT task threshold

This appendix reports the results of an experiment that was concerned with the shape of ERPs recorded when subjects were performing trials at, or near, threshold on the IT task. IT has usually been estimated for high levels of accuracy on the task. This practice has been justified because of the theoretical underpinning of the model, as originally described by Vickers et al. (1972). In that description, a fixed periodicity of sampling of sensory input was assumed. According to this view, performance on a simple, two-choice, visual discrimination task is described by an ogival function with performance at chance level (i.e., probability of correct responding is .5) at a stimulus duration of zero. The ogive asymptotes at a stimulus duration equal to the period of the assumed sampling mechanism. The point where asymptote of the ogival function occurs is therefore IT. For practical purposes, IT was defined as that SOA where 97.5% of responses are correct (Nettelbeck, 1987, p.303). As White (1996), following Levy (1993), pointed out, a more common procedure in psychophysics is to define and estimate threshold at a level half-way between chance performance and errorless performance. In a two-choice task this threshold is 75%. One reason for this practice is that estimates are more accurate when made in the middle of the curve defining performance on the task, rather than at the upper tail of the curve (e.g., Regan, 1989, p.190). That this would be so can be seen from examining Figure A3.1. Even small differences in the upper tail of the curve would give rise to a substantial change in the threshold estimate. Conversely, in the steep part of the curve the opposite is the case.

The adaptive staircase procedures (e.g., Wetherill & Levitt, 1965) commonly used to estimate IT achieve their efficiency, in terms of the number of trials taken to reach an estimate, by presenting trials at SOAs that vary according to the subject's performance. Thus, in the implementation of Wetherill and Levitt's procedure used in this thesis and elsewhere (e.g., Nettelbeck & Rabbitt, 1992) the initial trial has an SOA of 250 ms. SOAs are successively reduced by 17 ms (i.e., the time to refresh the video monitor display) until an error is made. Subsequent SOAs are adjusted depending on the accuracy of the subject's performance. From the point where the first error is made, the SOA is reduced by 17 ms only after six consecutive correct responses are made, but the SOA is increased by 17 ms after a single error is made. The IT estimate (at the 90% level) is calculated as the mean of the next eight SOAs (after the initial error is made) where a reversal of direction of adaptation has occurred. It can be seen then that the trials are presented at SOAs that, for each subject, are on the steeper parts of the psychometric function, rather than on the tails of the function.

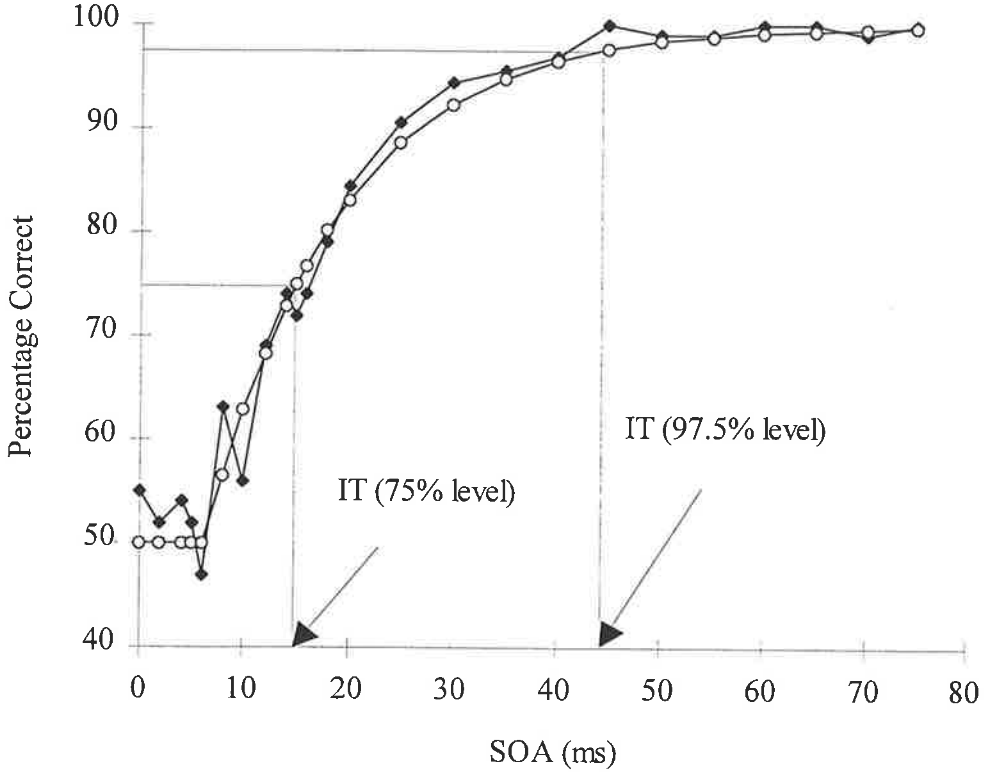

Figure A3.1. Typical psychometric function for the IT task. Filled symbols are observed data, open circles are fitted function. Lines indicate two different levels of threshold. Instability in performance will have less effect on an estimate of the 75% level threshold because this part of the curve is much steeper. Data from Burns, Nettelbeck and White (1998).

Caryl and Harper (1996) presented some data on the question of whether ERPs recorded during IT performance are affected by task difficulty (see Chapter 5 of this thesis for details). On the basis of their results Caryl and Harper (p.20) suggested that only "with reluctance" should ERPs be recorded when IT was being estimated by an adaptive procedure. Caryl and Harper cautioned that if adaptive procedures were used, account should be taken of the possibility that task difficulty and task threshold may be confounded in this procedure. (That is, according to Caryl and Harper, subjects with a lower IT will receive trials that are more difficult).

As was suggested in Chapter 5, when trials are presented on the steep portion of the psychometric curve defining performance on the IT task (i.e., at SOAs such that between about 65% and 85% of trials are discriminated correctly), as is the case when estimating IT by adaptive staircase procedures, then ERPs will be recorded to trials that have been discriminated either correctly or incorrectly. The question arises as to whether these ERPs are of a different shape from each other and, if so, whether they are different in the latency range identified by Caryl and co-workers as being important in correlations between ERPs and IT. A further question is whether ERPs for these trials are of a different shape from those for trials recorded to SOAs that correspond to the two extreme ends of the psychometric curve (i.e., at SOAs such that, effectively, either 50% or 100% of trials are discriminated correctly). Of particular concern is whether the trials presented during the adaptive phase of the estimation procedure are associated with ERPs that are different from those presented during the initial phase of estimation (i.e., trials which are on the upper tail of the curve and are therefore easy for all subjects).

Caryl's results (Caryl, 1994; Caryl et al., 1995; Caryl & Harper, 1996) suggested that if any differences exist in ERPs recorded to IT trials at different levels of difficulty, then it is likely that such differences will be found in the P300 region of the ERPs. Earlier work by Burns (1993) was consistent with Caryl's findings. These results are readily interpretable within the framework of what is known about factors that influence P300 latency and amplitude.[50] It should also be noted that, as discussed in Chapter 5, differences in this region would not be important for calculation of correlations of IT with ERP measures because previous work has not found robust relationships between IT and P300.

The P300 is a "large (ca. 10-20μV), positive-going potential with a latency of approximately 300 ms when elicited with a simple auditory discrimination task, and is of maximal amplitude over the midline central and parietal scalp areas" (Polich, 1989). The P300 has been associated with many different cognitive variables including: stimulus evaluation, task relevance, information delivery, resolution of uncertainty, discrimination, and meaningfulness (Johnson, 1988, pp.69-70; Polich & Kok, 1995, pp.106-107; Regan 1989, p.210). According to Regan (1989, p.237) "a P300 will be produced by task-relevant visual stimuli that occur somewhat unexpectedly and require a motor response or cognitive decision."

There are several theories on P300 amplitude. These include Desmedt's (1981) theory that P300 is related to 'closure' of perceptual events, and Donchin's (Donchin & Coles, 1988) 'context updating' theory. The latter theory is the most widely accepted (Polich & Kok, 1995). Johnson (1988) has proposed a theory that accounts for all factors that influence P300 amplitude by categorising those factors along three dimensions: (1) subjective probability; (2) stimulus meaning; and (3) information transmission.[51] This theory is therefore consistent with, and provides an extension of, Donchin's theory.

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[50] That is, ERPs recorded to presentations of the IT target that have different behavioural outcomes (i.e., correct or incorrect discrimination) will be different. This prediction is made with reference to theories of the P300 that are couched in information processing terms; this seems reasonable given the nature of the IT task.

[51] In earlier work (Burns, 1993), the current author used Johnson's formulation:

$$\text{P300 Amplitude} = f[T(1/P + M)],$$

where T represents the proportion of transmitted information, P represents subjective probability, and M represents stimulus meaning (Johnson, 1988, p.72) to predict P300 amplitude differences for IT stimuli presented at the extremes of the psychometric function defining IT performance.

P300 latency is usually interpreted as reflecting stimulus classification speed or, equivalently, stimulus evaluation time (Polich & Kok, 1995; Regan, 1989, p.239). However, P300 latency does not necessarily correlate with reaction time (Donchin, 1979).

The experiment described here was conceived with the aim of ascertaining whether IT trials, which are presented at SOAs such that they fall on the steep part of the psychometric function (i.e., that part of the function where trials are presented during the adaptive phase of IT estimation procedures), are associated with ERPs that differ according to whether the outcome of the trial is a correct or an incorrect discrimination. It was also designed to determine whether these trials are associated with ERPs that differ from those associated with trials presented at the tails of the psychometric function (particularly those presented at the upper tail).

No prediction was made with regard to the first mentioned aim of the experiment because this was an exploratory study. With respect to the second aim, it was expected that trials presented at the upper tail of the curve would be associated with ERPs showing a P300. This prediction was based on both Caryl's (1994) and Burns' (1993) findings and is consistent with theories of P300 amplitude discussed above.

In line with the foregoing discussion, if the shape of the ERPs recorded on the steep portion of the psychometric function defining IT performance are unaffected by whether the discrimination is correctly made or not, and more particularly if no difference exists in the earlier epoch of the ERP (at latencies of about 200 ms, or less) then ERPs can be confidently recorded during estimation of IT by an adaptive staircase procedure. The ERPs so recorded would be valid for testing correlations of ERP measures with IT and cognitive ability measures. Such a finding would be consistent with the results reported by Caryl and Harper (1996, see discussion in Chapter 5), because they found no effect of task difficulty on ERPs recorded from IT trials until after the P200 deflection.

Method

Subjects.

There were two subjects. The male participant was aged 35 years and the female participant was aged 20 years. Both subjects were familiar with the IT task and with ERP recording procedures.

Apparatus and Materials.

EEG was recorded in a lead-plated cubicle (as described in Chapter 3) lit at an intensity of 35 lx. EEG was recorded from the following sites: O1, O2, P3, P4, Cz, F3, and F4 (International 10/20 system, see Figure 3.1). One channel of EOG was recorded from an electrode attached in the pupillary line just above the eyebrow of the left eye. All channels were referred to the left ear lobe; the subject was earthed via the right ear lobe. Amplifier gain was set at 10,000 with analogue filters set 0.2 - 100 Hz; the 50 Hz notch filter was not used in these recordings.

Because this experiment required the presentation of IT stimuli at SOAs such that performance was at about 75% accuracy, millisecond control over SOAs was required. Video monitors are limited by their refresh rate to presenting stimuli in multiples of the time taken to refresh the display. For this reason, IT stimuli were presented on a light-emitting diode (LED) display. Yellow, rectangular (5 mm x 2 mm) LEDs were embedded, flush with the surface, in a 240 mm square of sheet metal, painted matt black. At a nominal input of 20 mA each LED lit at an intensity of 4 mcd. The display consisted of seven elements (Figure A3.2). Each element consisted of four LEDs, assembled end-to-end with gaps of 10 mm between the elements.[52] At the viewing distance of 2 m, one element of the display subtended a visual angle of 0.4 deg.

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[52] The rationale for introducing gaps into the IT target figure and mask is described in Burns et al. (1998). Briefly, it has long been recognised that, at least for some people, the traditional IT display provides

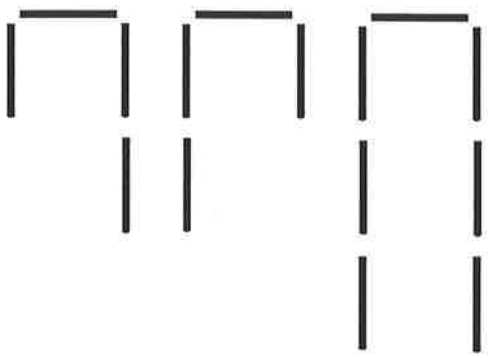

Figure A3.2. Segmented IT target figures (left and centre) and segmented mask used in the experiment reported in Appendix III.

Each target comprised four of the top five elements of the array, configured as either the left or middle illustration in Figure A3.2. Following the variable SOA, the remaining elements of the display were lit, thereby creating a backward mask (see right-hand illustration in Figure A3.2) and all the elements remained lit so that the total time from target onset to mask offset was 550 ms. The subjects signalled, with the corresponding hand, on which side of the target figure the shorter line had appeared by pressing the corresponding button on a bar which rested on the arms of the chair in which they were seated.

Design and Procedure

Both subjects had completed IT estimation during participation in one of the experiments reported elsewhere in this thesis—that is, estimations involving IT presentations on a video monitor and with the 'flash mask' of Evans & Nettelbeck (1993). These estimates made at the 90% level were converted to equivalent values at the 75% level (Nettelbeck,

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subtle visual cues that obviate the necessity of making a judgement on line-length (Nettelbeck, 1987). One of these cues has been described as line-end flicker (White, 1996). This cue is reported as a flicker or flash at the ends of the legs of the IT target when the target figure is replaced with the mask. The segmentation of the figure was introduced to provide irrelevant flicker cues thereby rendering the use of the cues more difficult. Results reported by Burns et al. suggested that the segmentation was only partially effective in reducing use of this cue. The performance of one of their subjects was unaffected by segmentation. Their other two subjects were affected in varying but small degree.

1987. p.307) so as to provide an initial value for locating an SOA where performance was reliably in the required range . Subjects attended three recording sessions on separate days over a period of about one week. For the first session only, after subjects were prepared for EEG recording a series of practice trials were presented on the LED display (the subjects had not seen this version of the IT task before). After familiarisation with the display, five series of 20 trials each were presented. The SOAs of these series began at the 75% level calculated from the subject's previously determined (90% level) IT estimate. After each series of 20 trials, performance was monitored and the SOA for the next series was adjusted by 5 ms in either direction so that performance would fall between 70% to 80% of trials correct. The last one or two series served to confirm that an appropriate SOA had been identified (i.e., subjects made between 70% and 80% correct discriminations). The subjects were unaware that this was the aim of the procedure and they were told that these were merely practice trials. For subsequent sessions a shorter series of practice trials was completed.

After completion of these familiarisation trials, EEG recording commenced. Subjects were told that a series of trials of varying difficulty would be presented. They were requested to respond in the usual fashion. That is, accuracy of responding was emphasised as being most important. Subjects were told that if they were unsure which leg of the IT target was shorter they should guess.

At each session 224 trials were presented. There were three types of trials: (1) 56 trials with an SOA of 1 ms; (2) 112 trials with an SOA set at the level where the subject's performance was reliably between 70-80% accurate across all trials; (3) 56 trials with an SOA of 250 ms. These trials will be referred to hereafter as IT_50, IT_75, and IT_100, respectively, the numbering referring to the level of accuracy of responding (i.e., percentage of trials correctly discriminated) expected in each condition. For all trials the total duration of target and mask was 550 ms. Trials were presented in random order with an interval of 2.5 s between the subject's response and the next trial.

EEG recording epochs were 2.5 s in duration beginning 0.5 s prior to the onset of the IT target. Sampling rate was 400 Hz. All EEG processing was done with SCAN software as follows. First, a 30 Hz low-pass filter (–6db at 30 Hz) with a slope of 24 dB/octave was applied and then a prestimulus baseline of 250 ms prior to stimulus onset was established. Next, an ocular artefact reduction algorithm was implemented[53]. This procedure was adopted in preference to excluding trials during which an eye blink had occurred because it was important that as many trials as possible be used to construct the ERPs (especially for the incorrect responses to IT_75 trials). Five separate ERPs were constructed: (1) an ERP for all IT_50 trials; (2) an ERP for IT_75 trials that were not discriminated correctly; (3) an ERP for IT_75 trials that were discriminated correctly; (4) an ERP for all IT_75 trials; (5) an ERP for all IT_100 trials. These ERPs will be referred to hereafter as IT_50, IT_75(I), IT_75(C), IT_75(A), and IT_100.

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[53] Ocular artefact reduction algorithms generally subtract a fraction of the EOG from the EEG. The SCAN software implements the ocular artefact reduction algorithm of Semlitsch et al., (1986). This correction procedure employs regression analyses. Briefly, EEG and EOG epochs containing eyeblinks are averaged and then a regression coefficient

$$\beta = \text{covariance(EEG, EOG)/variance(EEG)}$$

is calculated for each EEG channel. The EOG is then subtracted from the single sweep EEG data so that

$$\text{'corrected' EEG} = \text{'raw' EEG} - \beta(\text{EOG}).$$

The implementation of the algorithm within SCAN requires an approximate average duration of eye blink for each individual. This was estimated for each subject by measuring (from the EOG channel) the duration of the first 10 eyeblinks recorded.

The effectiveness of the algorithm can be assessed by reviewing the transmission coefficients (i.e., β) and the *SD* of β. It is recommended in the SCAN manual that $SD(\beta)$ be less than 0.05 µV. In this experiment, $SD(\beta)$ was always less than or equal to 0.002 µV.

Results

Table A3.1 shows the percentage of correct trials for each condition over the three sessions for each subject.

Table A3.1

Percentage of correct trials in three conditions for two subjects over three experimental sessions

	Subject	
Condition	A	B
IT_50	46.4	45.8
IT_75	77.4	81.5
IT_100	100	100

Note. The SOAs for condition IT_75 were 30 ms and 26 ms for subjects A and B, respectively.

It can be seen that performance was at chance level for IT_50 and perfect for IT_100. For IT_75, both subjects failed to discriminate correctly about 20% of trials. Reference to Figure A3.1 shows that this level of performance is on the steep part of the psychometric function defining IT performance.

Figures A3.3 and A3.4 show four ERPs from seven electrode sites for each subject. The ERPs are for the IT_50, IT_75(I), IT_75(C) and IT_100 conditions, respectively. For both subjects, the presence of a P300 in the IT_100 condition is readily apparent.

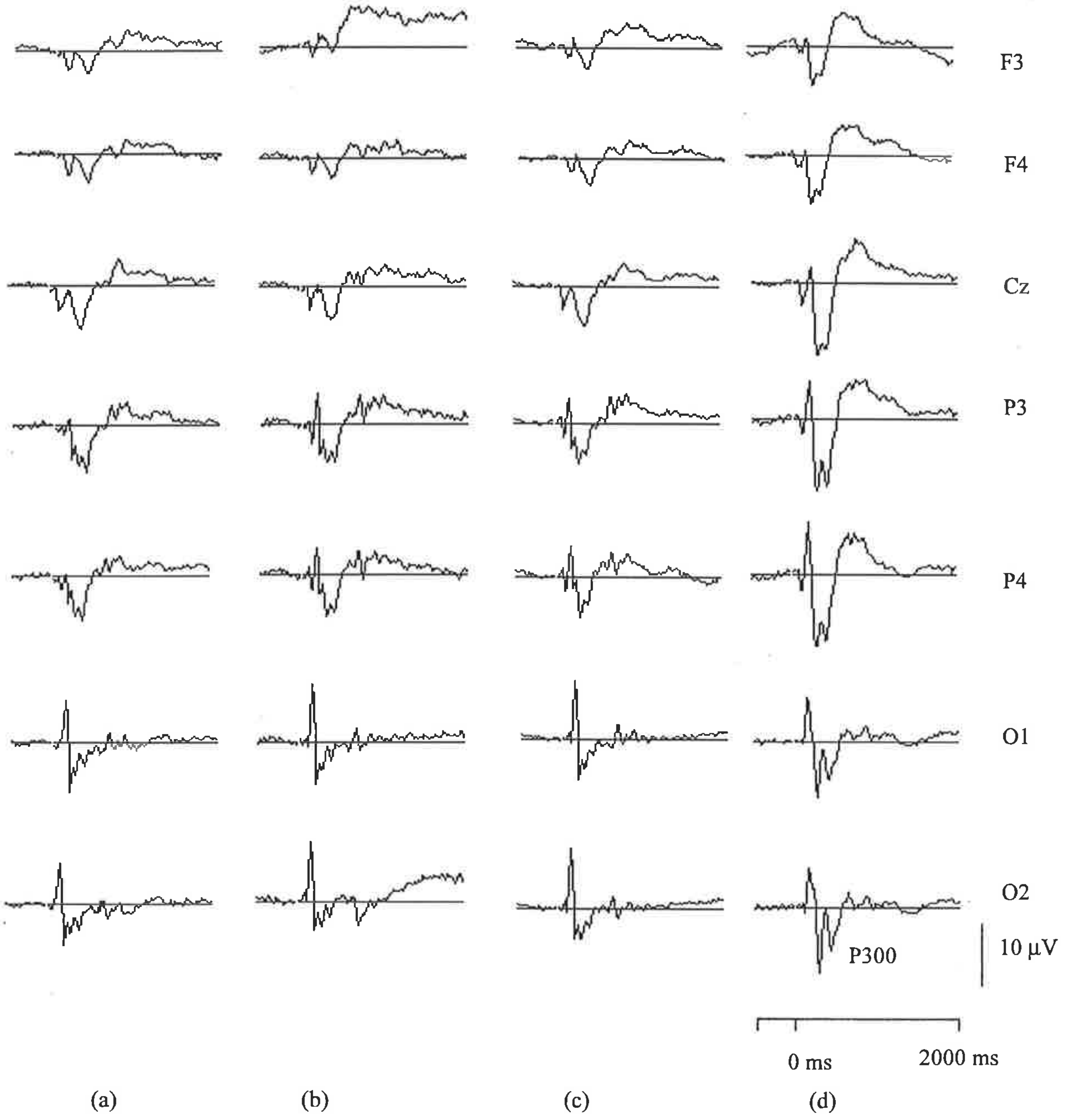

Figure A3.3. ERPs from seven electrode sites for subject A. Traces start 500 ms prior to onset of IT target figure. (a) condition IT_50; (b) condition IT_75(I) i.e., trials incorrectly discriminated; (c) condition IT_75(C) i.e., trials correctly discriminated; (d) condition IT_100.

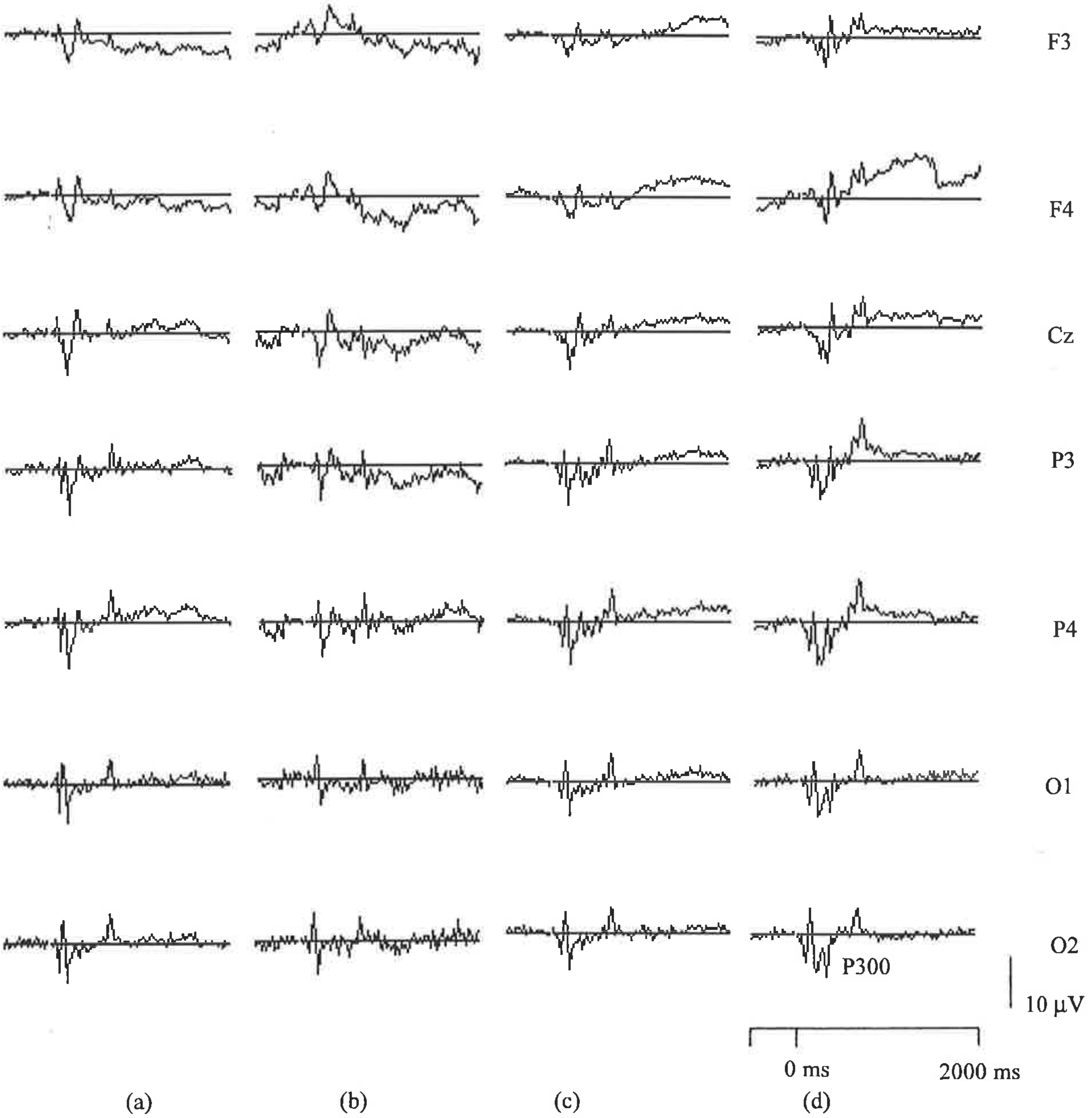

Figure A3.4. ERPs from seven electrode sites for subject B. Traces start 500 ms prior to onset of IT target figure. (a) condition IT_50; (b) condition IT_75(I) i.e., trials incorrectly discriminated; (c) condition IT_75(C) i.e., trials correctly discriminated; (d) condition IT_100.

To assess whether ERP waveforms differed from each other, difference waveforms were computed, by subtraction. For these difference waveforms, the voltage at each time point was compared with zero by a simple t-test. That is, if there were no difference between two waveforms at a particular time point then the difference waveform voltage, at that time point, would not differ significantly from zero. Such testing can determine, for example, whether a P300 is present in one condition but absent in another. It can also define latencies at which two waveforms differ from each other when, for example, the outcomes of the responses to trials associated with those waveforms are different. With data of this form, however, consecutive time points are not independent. Moreover, Bonferroni corrections for the calculation of multiple t-test comparisons are also not appropriate. This is because the power of the statistical test would be greatly reduced. To overcome such an objection to this method, and for the purposes of these analyses, only the epoch up to 500 ms after the onset of the IT target was considered. Further, the difference waveform was required to be significantly different from zero at a relatively conservative level (i.e., $p < .01$, two-tailed) for a sequence of points corresponding to 10 ms duration before it was considered likely to be a nonrandom divergence between conditions. While it is appreciated that these criteria are arbitrary, they accord well with the recommendations of Guthrie and Buchwald (1991) for the testing of difference potentials between groups of subjects when the ERP waveforms have a high autocorrelation.

The first comparison made was between the IT_75(I) and IT_75(C) waveforms. Figures A3.5 and A3.6 show the t-values plotted against time after IT target onset for electrode Cz, separately,[54] and for all electrodes together, for each subject. The waveforms were not significantly different from zero for either subject. The conclusion drawn was that

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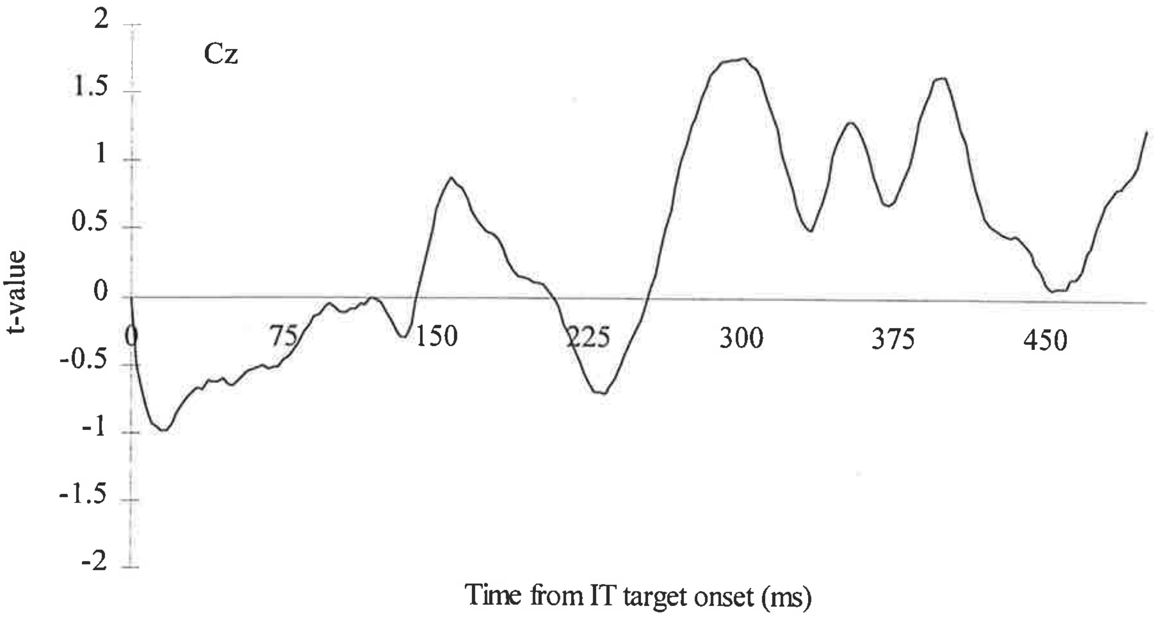
[54] These waveforms are presented separately to enable direct comparison with the work of Caryl, who has recorded solely from the Cz site.

the waveforms for correct versus incorrect discriminations did not differ in a way likely to affect calculation of correlations with IT.

Because the waveforms for IT_75(C) and IT_75(I) did not differ, the EEG recorded to all trials at this SOA can be averaged together. The remaining comparisons are therefore made with IT_75(A).

First, comparisons of IT_75(A) with IT_100 were made. This comparison corresponds to comparing ERPs from trials recorded during the adaptive phase of IT estimation with ERPs from trials recorded during the initial phase of estimation. Figures A3.7 and A3.8 show the t-values plotted against time after IT target onset for electrode Cz, separately, and for all electrodes together, for each subject. Clearly, as predicted, for both subjects the waveforms were different. This difference is most marked in the region of the P300. However, subject A also showed differences at earlier latencies; the waveforms begin to differ at 195-200 ms, at site Cz, and as early as 125 ms at the occipital sites. The findings at site Cz are consistent with those of Caryl (Caryl et al., 1995; Caryl & Harper, 1996). That is, differences do not appear until about 200 ms after the onset of the IT target figure. However, this finding does not hold for all sites.



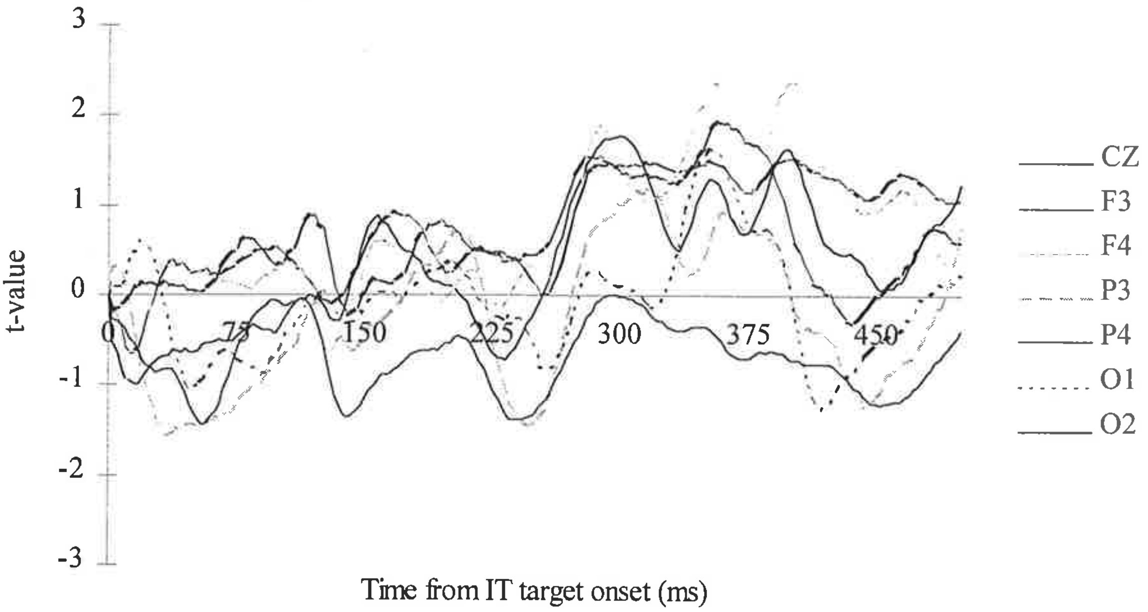


Figure A3.5. Plot of t values against time after onset of IT target for difference waveform for conditions IT_75(C) and IT_75(I) for subject A. Top panel shows electrode site Cz. Bottom panel shows all electrode sites together. Nominal t value ($p < .01$, two-tailed) to be significant is 2.58.

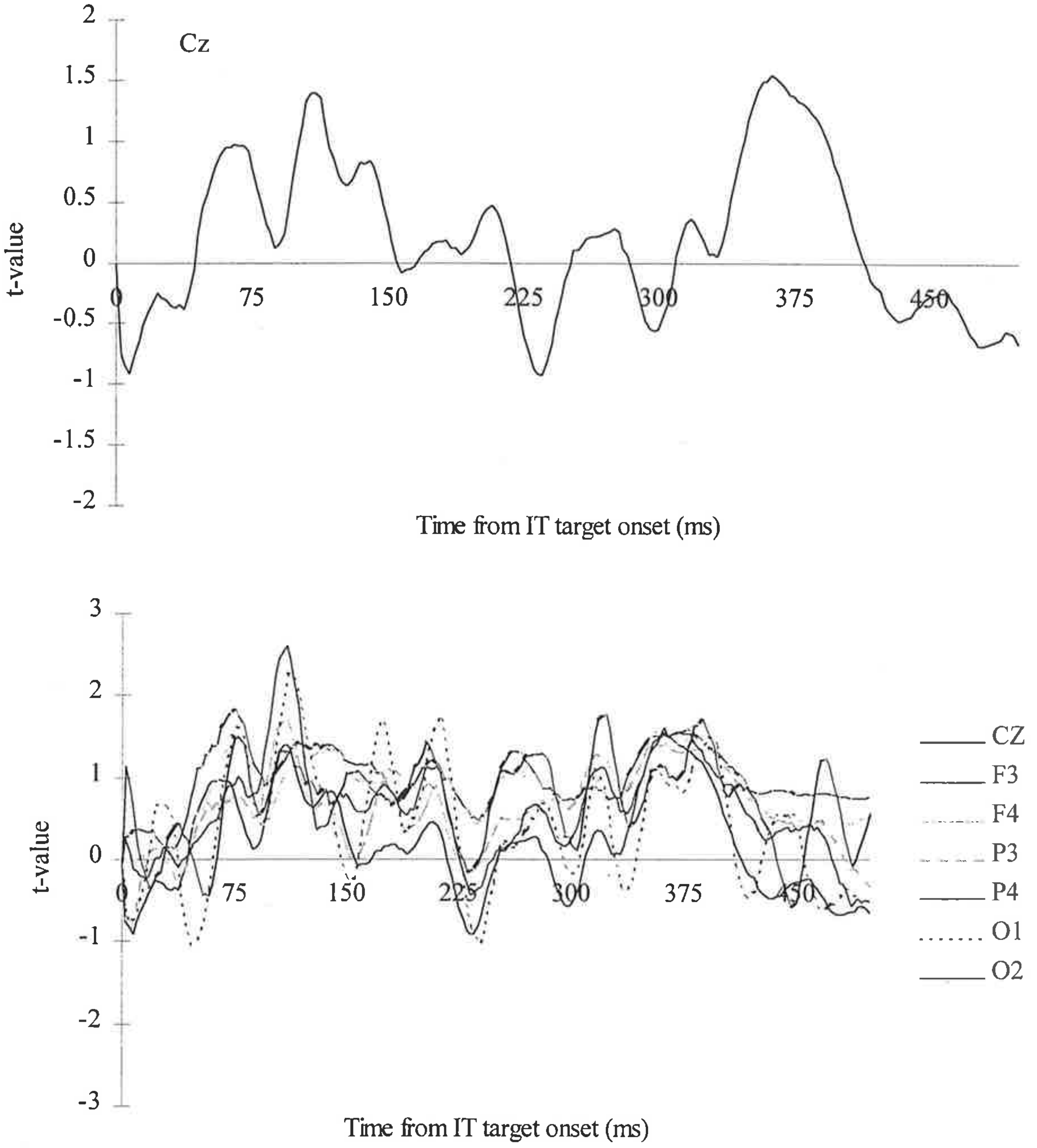
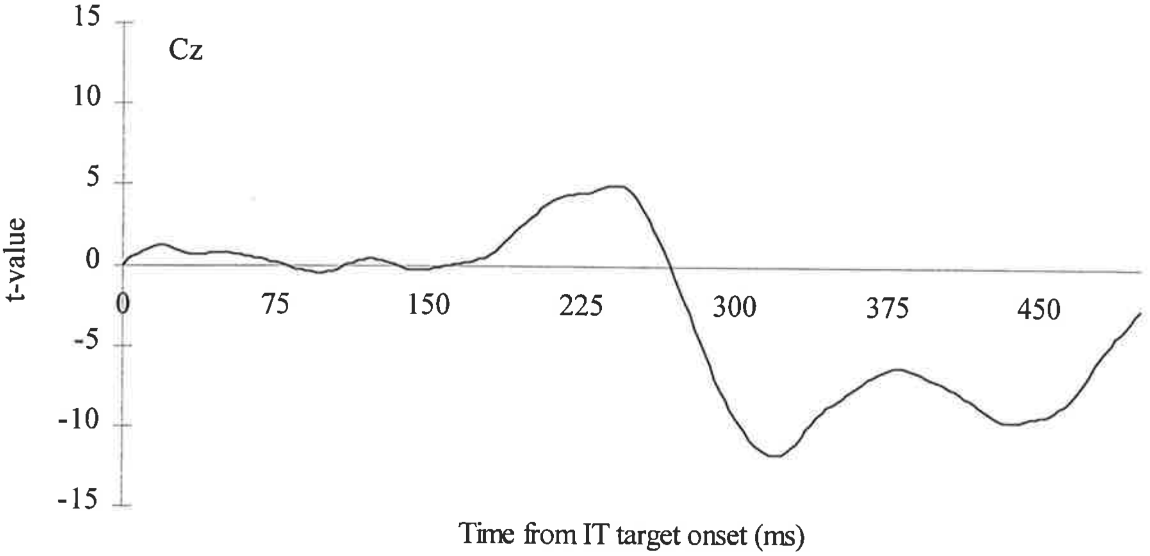


Figure A3.6 Plot of t values against time after onset of IT target for difference waveform for conditions IT_75(C) and IT_75(I) for subject B. Top panel shows electrode site Cz. Bottom panel shows all electrode sites together. Nominal t value (*p* < .01, two-tailed) to be significant is 2.58.



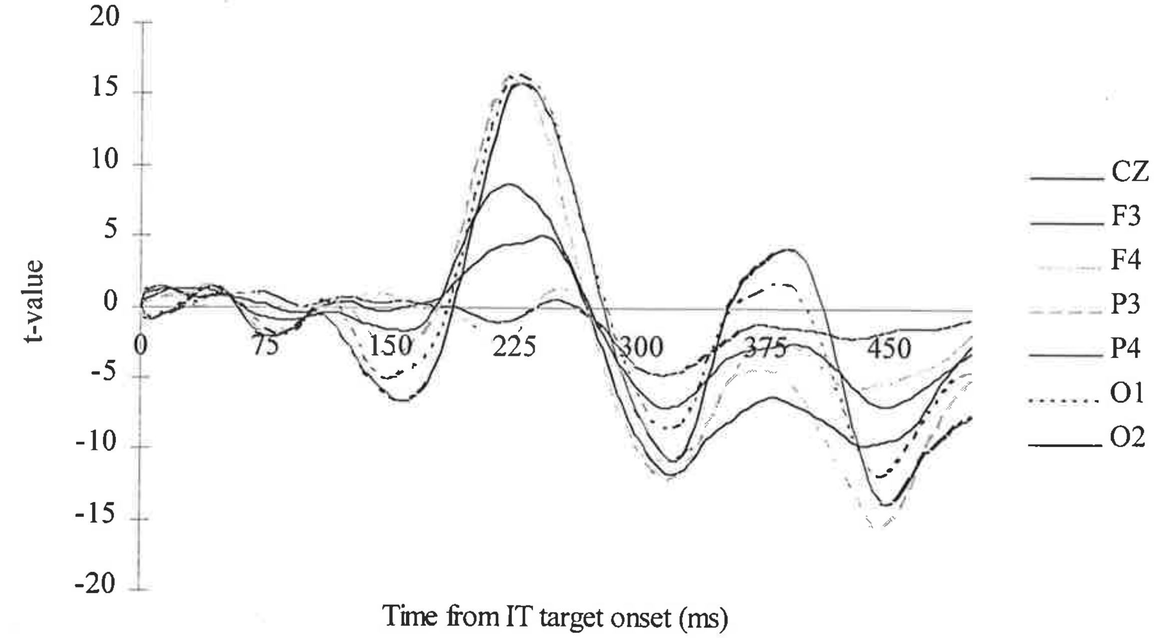


Figure A3.7. Plot of t values against time after onset of IT target for difference waveform for conditions IT_75(A) and IT_100 for subject A. Top panel shows electrode site Cz. Bottom panel shows all electrode sites together. Nominal t value ($p < .01$, two-tailed) to be significant is 2.58.

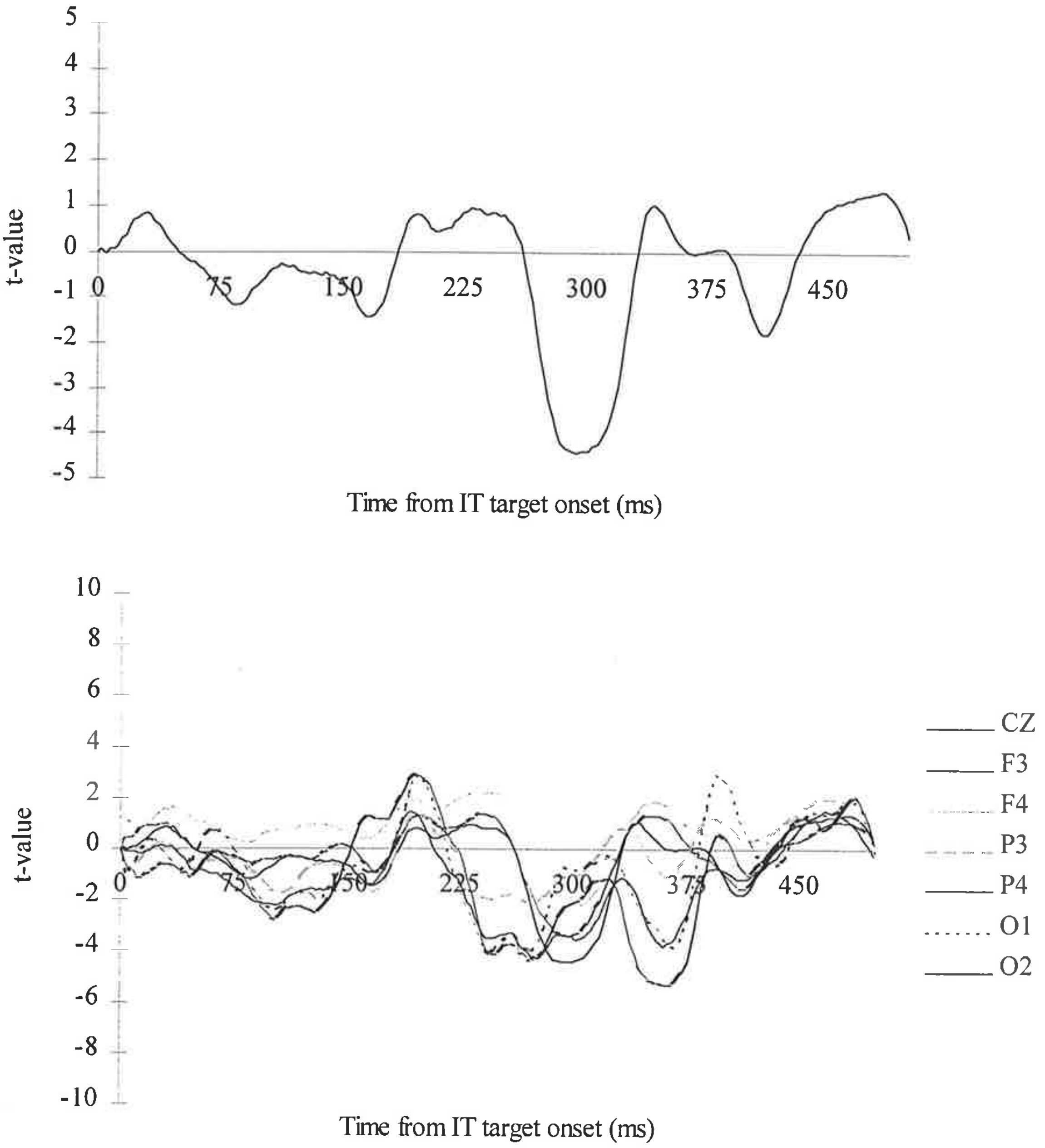
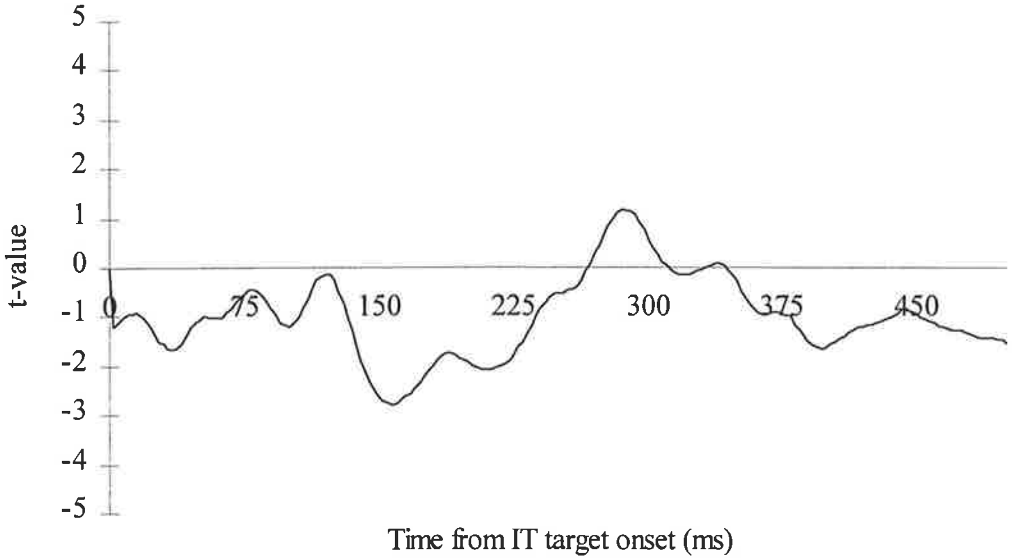


Figure A3.8. Plot of t values against time after onset of IT target for difference waveform for conditions IT_75(A) and IT_100 for subject B. Top panel shows electrode site Cz. Bottom panel shows all electrode sites together. Nominal t value (*p* < .01, two-tailed) to be significant is 2.58.



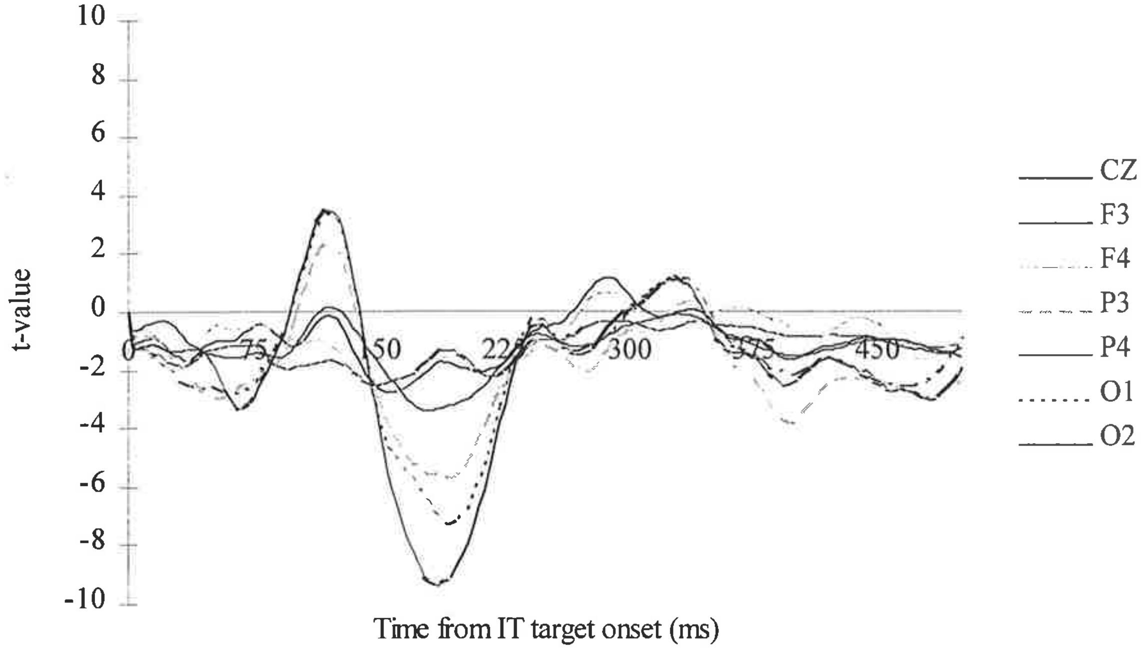
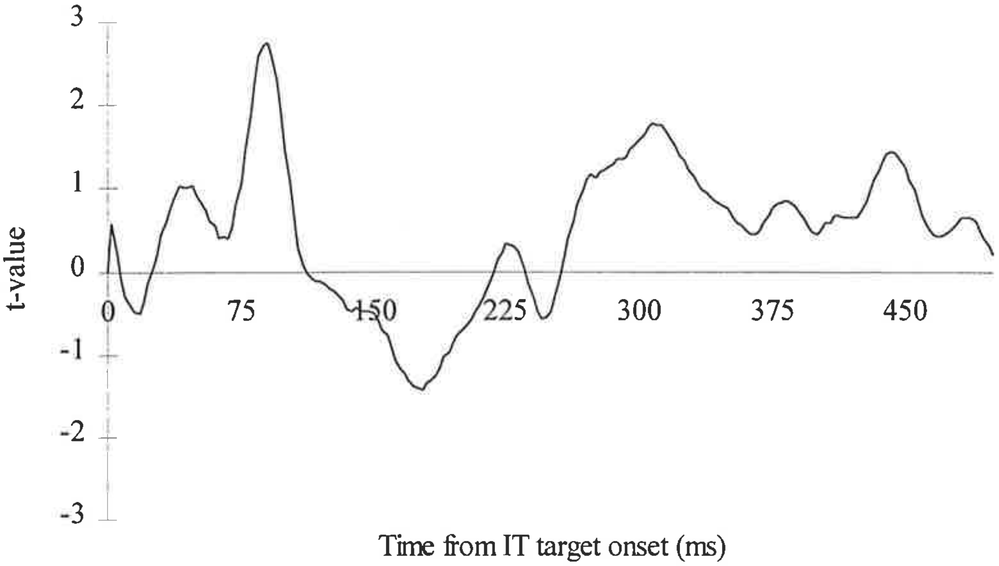


Figure A3.9. Plot of t values against time after onset of IT target for difference waveform for conditions IT_75(A) and IT_50 for subject A. Top panel shows electrode site Cz. Bottom panel shows all electrode sites together. Nominal t value (*p* < .01, two-tailed) to be significant is 2.58.



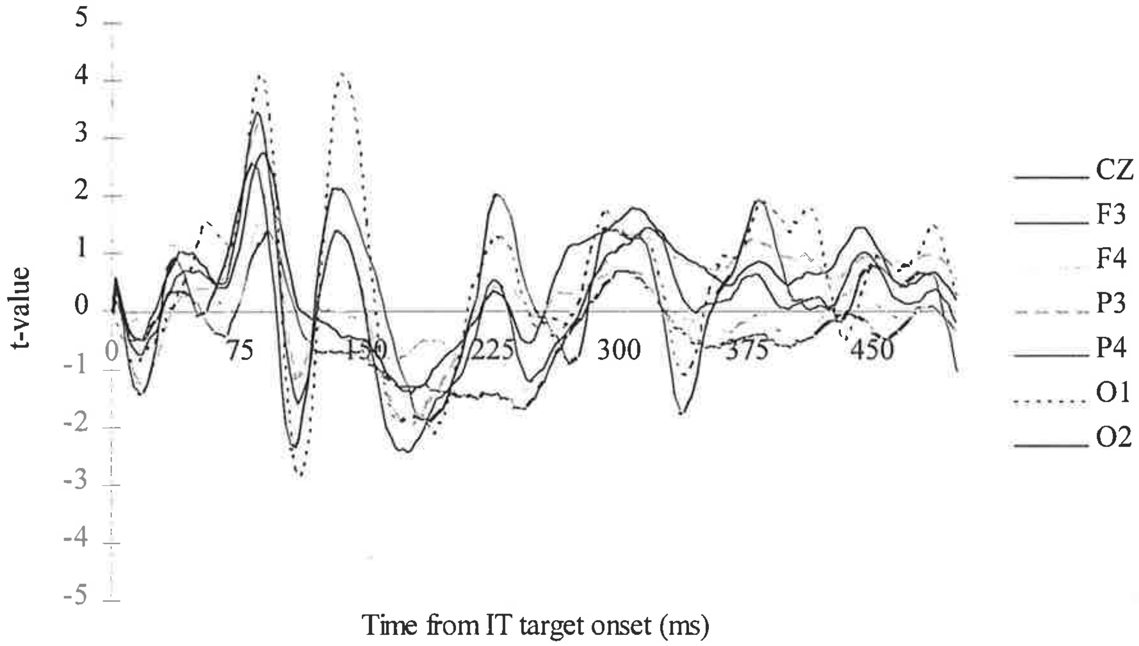


Figure A3.10. Plot of t values against time after onset of IT target for difference waveform for conditions IT_75(A) and IT_50 for subject B. Top panel shows electrode site Cz. Bottom panel shows all electrode sites together. Nominal t value ($p < .01$, two-tailed) to be significant is 2.58.

Finally, comparisons of IT_75(A) with IT(50) were made. This comparison is not as relevant to the question of whether ERPs should be recorded during IT estimation by adaptive procedures. This is because few, if any, trials are presented at such short SOAs during estimation procedures. However, this condition was included for completeness.

Figures A3.9 and A3.10 show the t-values plotted against time after IT target onset for electrode Cz, separately, and for all electrodes together, for each subject. Subject A shows differences at the central, parietal and occipital sites at latencies in the range approximately 145 - 230 ms. Subject B shows differences at parietal and occipital sites at somewhat earlier latencies.

Discussion and conclusions

The aim of this experiment was to test whether ERPs associated with trials presented on the steep part of the psychometric function describing performance on the IT task differed according to whether the discrimination was made correctly or not. The reason for investigating this question was that Caryl and Harper (1996) suggested that ERPs should not be recorded when IT was estimated by adaptive staircase procedures. As discussed in Chapter 5 of this thesis, this suggestion was based on work showing that task difficulty and task threshold were confounded in an auditory pitch discrimination task. Caryl and Harper found no such effect for a visual IT task. The reason for the emphasis on trials presented on the steep part of the psychometric function was that this is where most trials are presented during IT estimation by adaptive staircase procedures. Adaptive staircase procedures, as used here and by others (e.g., Nettelbeck & Rabbitt, 1992), also incorporate a series of trials starting at latencies of about 250 ms. These trials are very easy for all subjects and thus fall on the upper tail of the psychometric function.

The main finding here was that, at an SOA such that about 20% of trials were not correctly discriminated, ERPs were the same irrespective of whether a correct or an incorrect response was made. This finding, from two subjects with different thresholds, means that

ERPs from trials presented on the steep part of the psychometric function will not confound task difficulty and task threshold.

The second finding was that trials with an SOA such that they fall on the upper tail of the psychometric function show a marked P300 deflection. These ERPs are different from those recorded to trials which fall on the steep part of the function. They are different in the region of the P300 at all electrode sites used. Further, one subject showed differences, at occipital sites, as early as 125 ms after the onset of the IT target. The findings here were consistent with those of Caryl and Harper (1996) who found that task difficulty did not affect ERPs (recorded at Cz) until after 200 ms. However, a conservative conclusion was drawn that because the ERPs from these long SOA trials may be different from the ERPs recorded during the adaptive phase of IT estimation then they should be excluded from construction of ERPs which are to be used for testing correlations of ERP measures with IT.

The third finding concerned trials with an SOA such that performance was at chance level. Again, ERPs from these trials differed from ERPs associated with trials which fall on the steep part of the function. However, few, if any, trials are presented at such SOAs during IT estimation. If the EEG associated with these few trials were included in an average waveform it would likely not affect ERP parameters used for testing correlations of ERP measures with IT.

In conclusion, Caryl and Harper's (1996) concern that the possible effect on ERP waveforms of confounding of task difficulty and task threshold during IT estimation by adaptive staircase procedures has been addressed. If the EEG associated with those trials presented during the initial phase of IT estimation (i.e., those trials with long SOAs) is excluded from the construction of ERPs then there will be no effect on ERP measures, particularly in the critical latency range of up to about 200 ms after the presentation of the IT target.

Appendix IV: Distributions of WJ-R test scores

Appendix IV shows the frequency distributions for scores on the WJ-R (see Chapter 7).

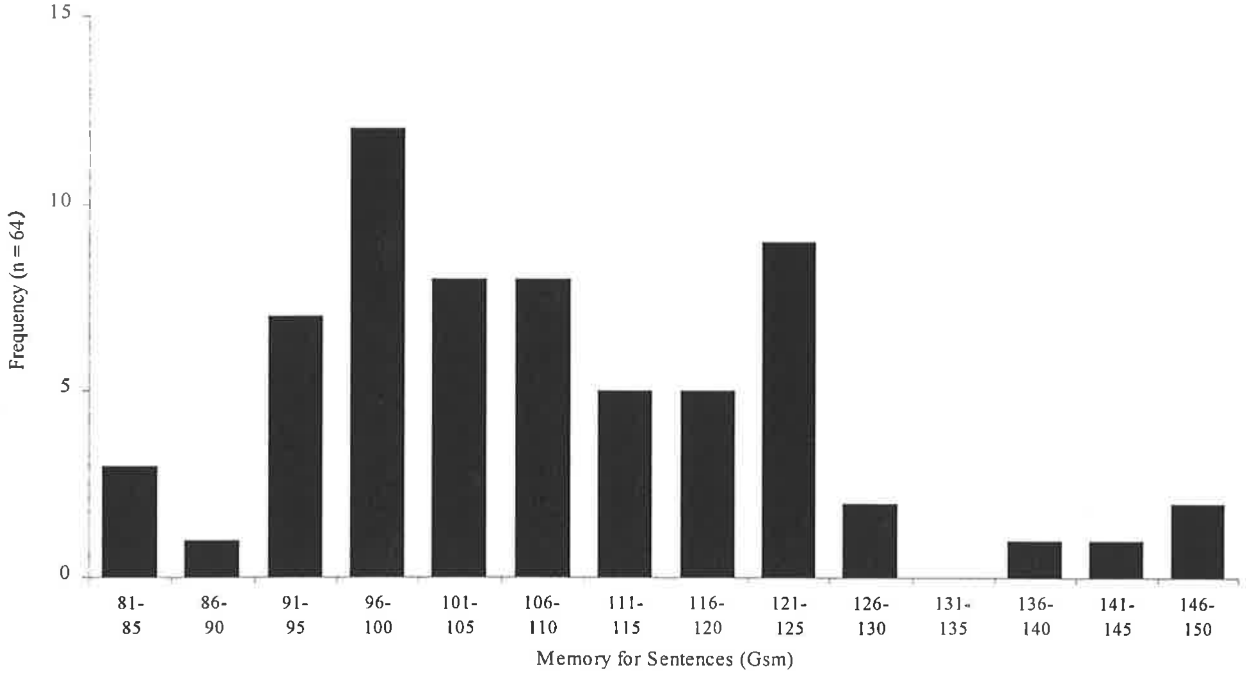


Figure A4.1. Frequency distribution for Memory for Sentences (Gsm) from the WJ-R; *N* = 64

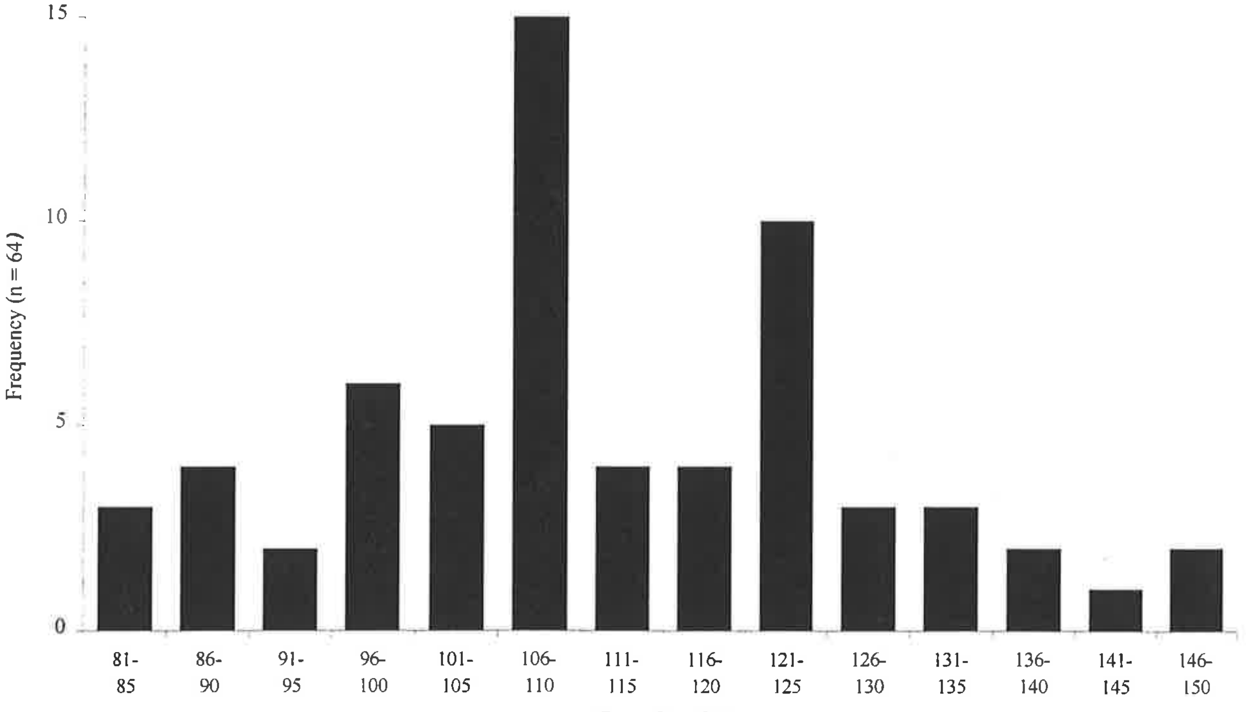


Figure A4.2. Frequency distribution for Cross Out (Gs) from the WJ-R; N = 64

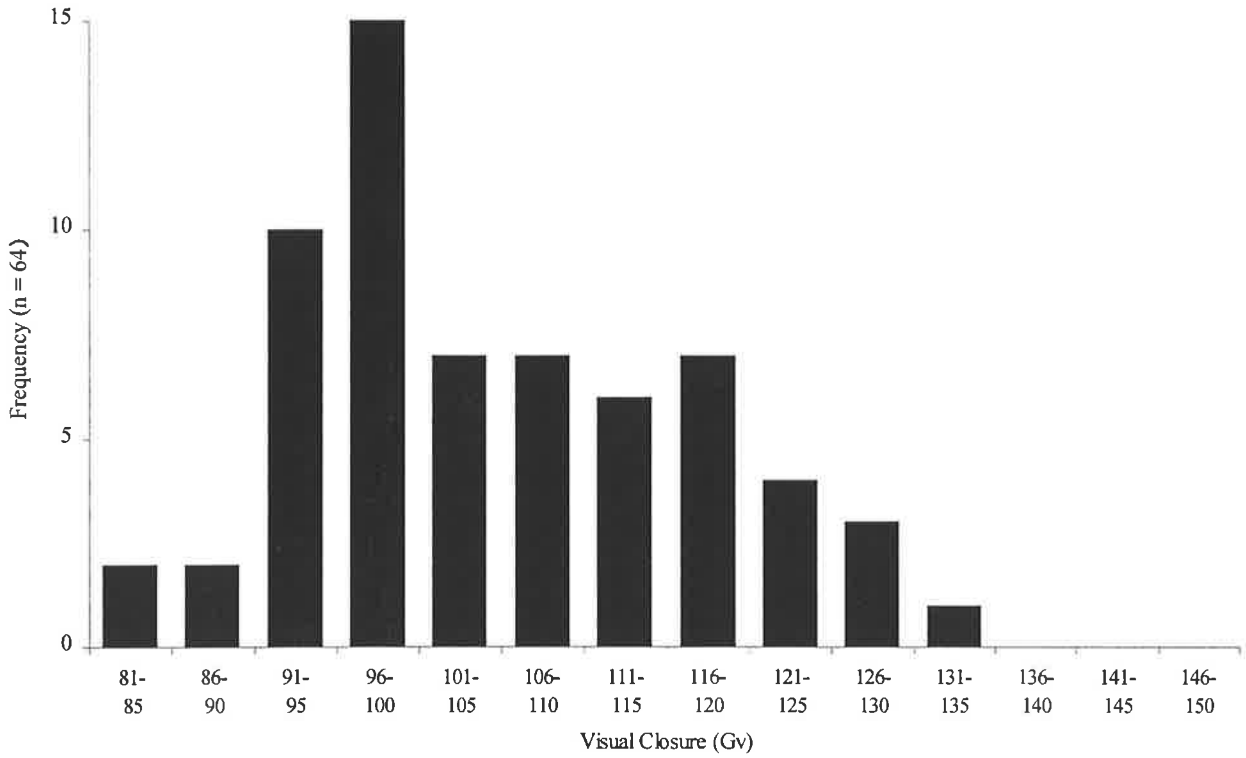


Figure A4.3. *Frequency distribution for Visual Closure (Gv) from the WJ-R; N = 64*

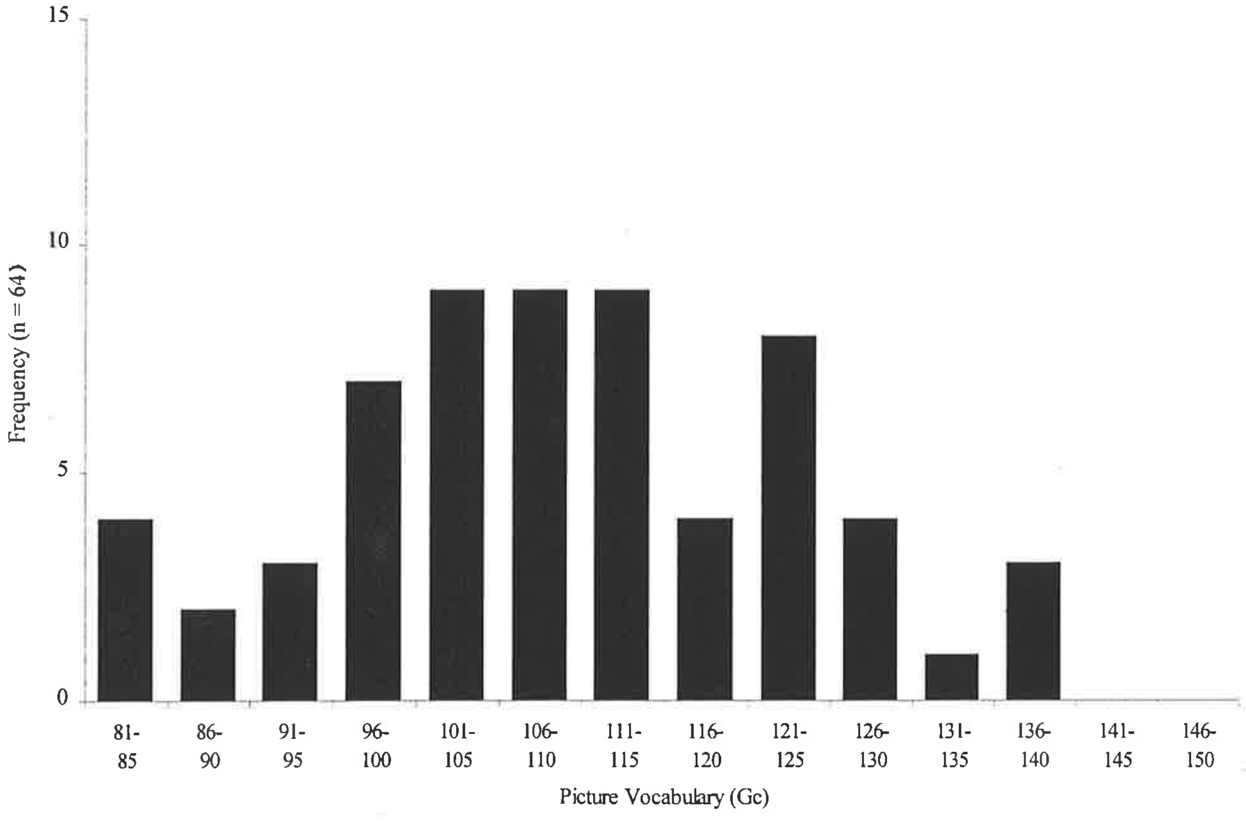


Figure A4.4. *Frequency distribution for Picture Vocabulary (Gc) from the WJ-R; N = 64*

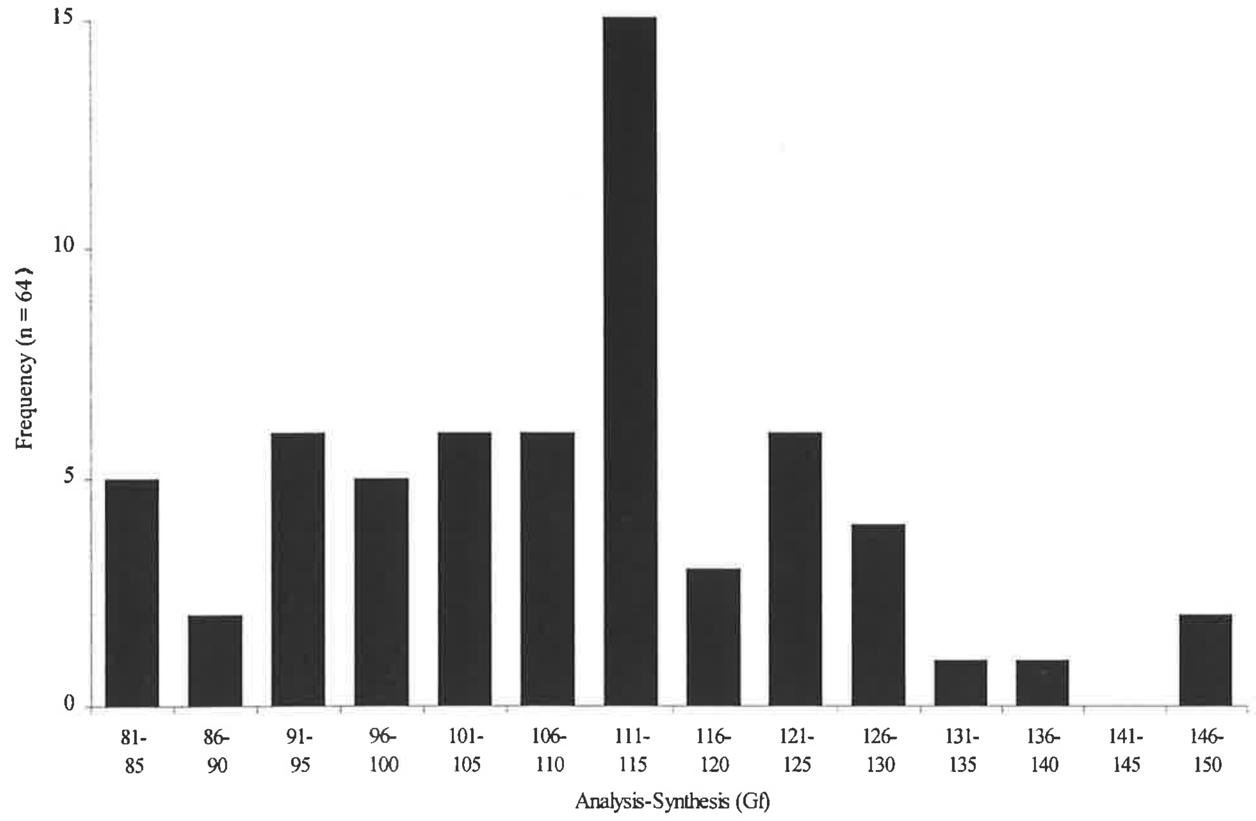


Figure A4.5. *Frequency distribution for Analysis-Synthesis (Gf) from the WJ-R; N = 64*

Appendix V: Zero-order correlations corresponding to partial correlations from Chapter 7

Appendix V presents the various raw correlations that correspond with the partial correlations presented in Chapter 7. These partial correlations were for the ERP deflection rise time measures whereby the effect of the amplitude of a deflection on the rise time was controlled. Chapter 7 gives full details on the rationale for using these partial correlations.

The correlation between N70 rise time and IT was .18 (p =.09, one-tailed); the correlation between P100 rise time and IT was –.03 (ns).

At site O1 the correlation between N1 rise time and IT was .07 (df = 56, ns); at site O2 the correlation was .06 (ns).

Table A5.1

Matrix of zero-order correlations between rise time measures from pattern reversal ERP and IT estimation ERP and WJ-R test scores

	MS	CO	VC	PV	AS
Pattern reversal ERP					
N70	–.07	–.23 *	.15	.12	.05
P100	–.05	–.03	.03	.02	–.05
IT estimation ERP					
N1 at site O1	.09	.02	.11	.05	–.00
N1 at site O2	.08	.03	.10	–.12	–.03

Note. MS = Memory for Sentences; CO = Cross Out; VC = Visual Closure; PV = Picture Vocabulary; AS = Analysis-Synthesis

**p* < .05, one-tailed

Table A5.2

Matrix of zero-order correlations between rise time measures and deflection latencies and NCVs calculated from pattern reversal ERPs

	Latency[a]		NCV[a]	
N70 rise time	.37	**	–.37	**
P100 rise time	.34	**	–.31	**

[a] The correlations are for the respective deflections. That is, the N70 rise time correlations are for the N70 latency and the NCV calculated from it.

** $p < .01$; one-tailed

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