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Mental Ability and Event-Related Potentials in an Auditory Oddball Task with Backward Masking: From Description to Explanation

by

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Abstract

The relation between mental ability and speed of auditory discrimination was investigated during an auditory oddball task with backward masking. Behavioural and electrophysiological data were collected from 58 females. Across target discrimination conditions that varied in the interval between the target and the masking stimuli and in the tonal frequency of the target and masking stimuli, HA participants displayed faster RT and more accurate discriminations than LA participants. HA participants also had shorter P300 and MMN latency and larger P300 amplitude than LA participants. The effects suggest that the speed of accessing STM is faster for HA than LA participants. Moreover, the pattern of results obtained with these data eschews task difficulty effects that would endorse a sensory discrimination hypothesis.

Introduction

Individual differences in abilities, values, attitudes, and expectations are important elements in our daily lives. The purpose of this project is to contribute to our understanding of individual differences in mental ability by applying cognitive and physiological methods.

During the past one hundred years, there has been considerable progress in the development of a descriptive typology of mental ability using psychometric methods. Specifically, there is a strong case for a unitary structure composed of two general factors, fluid and crystallized ability, that converge into a substantial general factor. This work is an important step towards a comprehensive and widely accepted standard that is a prerequisite for exploring mental ability.

The validity of mental ability tests has been established in educational, occupational, and mental health institutions. These descriptive measures are successfully applied in academic and personnel selection and in predicting social and economic achievement. The success in describing mental ability, however, has not been matched by comparable success in explaining the basis of the variation that is described.

Early in the 20th century, there were a number of attempts to establish the fundamental processes that determine individual differences in mental ability using simple tasks that involved sensory discrimination, reaction time (RT), and memory ability (Deary, 1988). In recent years, some success was achieved with simple and choice reaction time procedures which consistently demonstrate that mental ability is inversely related to the speed of processing on simple decision tasks and perceptual discrimination tasks.

Another successful paradigm is inspection time (IT). IT is defined as the minimum duration of exposure that is required for a participant to accurately discriminate between two stimuli which are easily discernable at longer durations. Typically, a backward masking stimulus follows the presentation of the test stimuli, and is thought to render the discrimination more difficult. For both visual and auditory studies, individuals with higher levels of IQ performed better on these IT tasks than lower ability individuals (Grudnik & Kranzler, 2001).

Behavioural measures such as RT and IT may be influenced by factors such as attention, motivation, and motor execution processes. Therefore, studies that exclusively employ behavioural measures are unable to clearly demonstrate whether higher ability participants have superior task performance, or if they simply have faster motor reflexes than lower ability participants. As a result, biological assessments of speed and accuracy of sensory discrimination have been used to complement behavioural measures.

Event-related potentials are ideally suited for an examination of the processes of mental chronometry at all stages of information processing. Notably, the P3 waveform is a positive wave that develops maximum peak amplitude at central and parietal sites at about 300 ms after the onset of a task specific stimulus (Pritchard, 1981). The P3 wave has proven to be a reliable index of the efficiency and speed of cognitive information processing (Johnson, 1986). P3 has been shown to correlate with mental ability in a series of cognitive psychophysiological studies (e.g. McGarry-Roberts, Stelmack, & Campbell, 1992). One limitation to the P3 waveform, however, is that it is attention-dependent and is potentially confounded by attention and motivation. As a result, an attention-independent event-related potential (ERP) measure would be a useful tool to study individual differences in mental ability.

From ERP recordings, an index of sensory discrimination termed mismatch negativity (MMN) is derived that is largely uninfluenced by the effects of attention or cognitive strategy (Näätänen, Gaillard, & Mantysalo, 1978). When ERP waveforms evoked by standard tones are subtracted from ERP waveforms evoked by deviant tones, a MMN wave indicating the discrimination of the deviant stimuli is evident. This ERP measure is an attention-independent index of processing speed at the sensory level. A recent study by Bazana and Stelmack (2002) revealed that higher ability participants had shorter MMN latencies than lower ability participants, indicating the individual differences may exist at a pre-sensory level.

In this thesis, the auditory oddball paradigm employed by Bazana and Stelmack (2002) will be adapted in an attempt to examine the fundamental nature of individual differences in mental ability. The role of processing speed and stimulus discrimination ability will be examined by collecting concurrent physiological and behavioural measures while research participants perform a stimulus discrimination task. Of particular interest is the role of the masking stimulus on task performance. Specifically, the impact of the masking stimulus on task performance will have a direct bearing on the theoretical framework employed to explain these results.

This thesis is divided into five chapters. In chapter one, the pathways of progress in mental ability research will be critically reviewed. Special attention will be paid to the theoretical underpinnings of these research endeavours, along with an examination of practical implications. Chapter two will focus on the rationale for the current study, along with the hypotheses. Chapter three will contain the methods section for both studies. Special attention will be paid to a series of variables that were strictly controlled. Chapter four contains the results section highlighting the findings in this thesis. Chapter five will involve a focused discussion of the findings and revisit the hypotheses, along with the application of these findings to a theory of mental ability. This section will also include strengths, limitations and future directions.

Chapter One

Pathways of Progress in Mental Ability Research

Contemporary research into individual differences in mental ability began in the late 1800s and has continued until the present day. Research on the fundamental determinants of mental ability follows a reductionist approach. Two pathways that have been followed were cognitive and biological reductionism (Deary & Caryl, 1997). Biological reductionism includes studies of mental ability that involve genetics (traditional and molecular), brain size, nerve conduction velocity (NCV), electroencephalograms (EEG) and evoked potentials (EPs), and biochemistry. Cognitive reductionism includes research on the associations between psychometric mental ability and parameters from various RT paradigms and psychophysical procedures, and these tend to be captured by the term "information processing" approaches (Vernon, 1987).

The purpose of this literature review is not to catalog previous findings, but to highlight the pathways of progress that have taken place over the last century. Special attention will be paid to the applicability of these previous findings to our contemporary understanding of mental ability.

The Heritability of Mental Ability

There is little doubt that individual differences in mental ability are influenced by a significant hereditary component. The broad heritability estimate of IQ is about 40% to 50% in children, 60% to 70% in adolescents, and over 80% in adults (Jensen, 1998). In the following section, we will briefly outline the results from behavioural genetics studies. Early results, along with the implications of the Human Genome Project will also be discussed.

Evidence of genetic influences on IQ. Heritability is defined as the proportion of the phenotypic variance in a trait that is due to genetic variance. Behavioural genetics use quantitative genetics methodology in order to determine the proportion of the total phenotypic variance attributable to various sources of genetic and environmental factors. A detailed account of the methods of behavioural genetics is found in Jensen (1998).

There is strong evidence that individual differences in mental ability are due, in large measure, to genetic factors. This evidence is summarized in Jensen (1998) as follows:

1. Monozygotic (MZ; identical twins) reared together are much more similar in IQ (r=.86) than dizygotic (DZ: fraternal twins) twins reared together (r=.60).
2. MZ twins reared apart are more similar in IQ (r=.75) than DZ twins reared together.
3. The IQs of adopted persons who have never known their biological parents are more highly correlated with the IQs of their biological parents than with their adoptive parents.
4. Unrelated persons who were reared together from infancy show a much lower IQ correlations (r=.25) with each other in early childhood than do biological siblings (r=.49). Furthermore, these unrelated persons show no IQ correlations in adolescence and adulthood (r=-.01).

The Human Genome Project. The Human Genome Project has been described as the crowning glory of the 20th century (Plomin, 2003). This project has provided a working draft of the sequence of the 3 million letters of DNA in the human genome. A full accounting of the Human Genome Project, along with a discussion of DNA, linkage methods, and allelic associations, is found in Plomin, DeFries, McClearn, and McGuffin (2001).

The heritability of complex traits such as mental ability is likely due to multiple genes of varying but small effect size rather than one gene or a few genes of major effect. Genes in a multiple gene system are inherited in the same way as other genes but they have been given a different name – Quantitative Trait Loci (QTL) – in order to highlight some important distinctions. Unlike single gene effects that are necessary and sufficient for the development of a trait or disorder, QTLs contribute interchangeably and additively. The QTL perspective is the molecular genetic version of the quantitative genetic perspective which assumes that genetic variance on complex traits such as mental ability is due to many genes of varying effect sizes (Plomin, 2003).

One study, called the IQ-QTL Project, involves a systematic search for QTLs associated with normal variation in IQ. The project uses an association design that compares the frequency of alleles in cases of high IQ individuals to low IQ individuals. The *IQ-QTL Project* has recently reported results from a preliminary genome scan of 1847 markers (Plomin, DeFries, McClearn, & McGuffin, 2001). The project, thus far, has only uncovered QTLs that explain less than 1% of the observed variance. However, the authors are confident that more genes will be discovered in the near future (Plomin, 2003).

Summary and conclusion. The well established fact that there is a large genetic component to individual differences in mental ability is itself sufficient proof that the observed population variance in scores on IQ tests reflects something other than the acquired bits of knowledge, skills, and strategies called for by such tests. It is implausible that those specific aspects of mental test items would be encoded in the DNA. Biological information transmitted in the genetic code of DNA is a prerequisite condition for the heritability of any characteristic, including IQ test scores. The human characteristics coded in DNA are products of an evolutionary process, long before specific information content of conventional IQ tests came into existence (Jensen, 1998). It is therefore reasonable to assume that the basis for individual differences in mental ability reside in a series of basic cognitive and physiological processes. The purpose of this study is to identify and examine these basic processes.

Psychometrics

In its infancy, the study of mental ability quickly diverged into two separate paths; a sensory/physiological path advocated by Sir Francis Galton, and a psychometrics path made popular by Alfred Binet. While the latter was an attempt to bring mental ability into the realm of everyday human existence, the former was an attempt to apply strict scientific principles to the study of mental ability and to determine its fundamental nature.

What is mental ability? The field of psychology is often confronted with the seemingly difficult task of studying concepts with unclear operational definitions. Never is this more apparent than in the study of mental ability. Dating back to 1921, a symposium on the definition of mental ability produced a considerable amount of definitions, but little agreement (Thorndike, 1921). In 1986, Sternberg and Detterman (1986) published a follow-up symposium. Although there were some areas of agreement, considerable areas of disagreement still remained. The most prevalent definitions of mental ability include:

1. Mental ability is the ability of an organism to adjust itself adequately to its environment.
2. Mental ability is the hereditary capacity to learn.
3. Mental ability is the ability to reason.
4. Mental ability is the ability to solve a wide variety of problems rapidly
5. Mental ability is what mental ability quotient (IQ) tests measure.

At first glance, the fifth definition, initially advocated by Boring (1923), appears to be a circuitous attempt to beg the question. However, this definition is also congruent with Spearman's argument that IQ tests measure whatever is in common to all tests that form a positive manifold; namely the *g factor*. Although we will never have a definite answer, Boring (1923) was probably claiming that mental ability is related to a psychometrically derived general mental ability.

In an attempt to clarify a general consensus on definition, Snyderman and Rothman (1987, 1988) found a good deal of agreement among 600-plus experts consulted; abstract thinking or reasoning was checked by 99.3% of respondents as important, problem solving ability by 97.7%, and capacity to use acquired knowledge by 96.0%.

Spearman (1927) advocated a radically different definition of mental ability. In his view, mental ability is related to mental energy and to cognitive processes he defined as involving the eduction of relations. The eduction of relations involves the ability to note the relations between two or more elements and to draw common inferences. As an example, Spearman noted that if a person knows that "all A is B", then the intelligent person can deduce that "some A is B". Mental ability is therefore not the accumulation of discreet facts, but rather the eduction of linkages between these facts.

Despite all this controversy, the modern consensus seems to be that a clear and unambiguous definition of mental ability is less important. Perhaps this whole exercise in definition is misconceived (Eysenck, 1994). All the definitions of the concept of mental ability deal with effects the concept may have; mental ability is that which enables us to think abstractly, to solve problems, to acquire knowledge, to adapt our behaviour to circumstances, to achieve goals, to code information, to manipulate symbols, to perform judgment, to apprehend experience, and so forth (Eysenck, 1976). Whatever it is, it is a capacity to carry out cognitive tasks successfully; it is a dispositional variable enabling the possessor to do all the things mentioned more or less successfully. Therefore, this effort at definition is focused on effects rather than ability, and mental ability is guided by ability.

Mental ability quotient (IQ) test development. The use of tests to predict future performance dates back to 200 BC during the Han period in China. Under decree from the emperor, examinations were developed and administered in order to select and assign potential employees seeking an occupation in the civil service (Hothersall, 1995). However, Alfred Binet is credited with the modern day initiation of IQ test development.

By the late 1800s, Galton had established a laboratory in London for the measurement of individual differences. He assumed that individuals with higher mental ability would have keener sensory discrimination capacities than individuals with lower mental ability (Galton, 1883). However, Binet was opposed to the attempt to measure mental ability by focusing on elementary cognitive processes. He was surprised by the considerable place reserved to sensations and simple processes and by the little attention paid to superior processes and practical implications (Binet & Henri, 1896).

Binet was appointed as scientific advisor to a commission studying the needs of developmentally delayed children in the French public school system in 1905. Binet and Simon (1905) published the first IQ test. Binet and Simon wanted to develop an instrument that would allow educators the opportunity to evaluate a child's level of cognitive functioning and to decide if the child could benefit from special educational opportunities. Binet subsequently published two major revisions to his test. The 1908 revision shifted to an emphasis on normal children and included specific age-related equivalents to each test. In 1911, Binet expanded the test using five items at each age level, allowing for the calculation of fractional mental age. Shortly thereafter, Stern (1912) developed a rudimentary IQ index that involved the ratio of mental age to chronological age, multiplied by 100.

Binet's scales were enthusiastically received by American psychologists. Goddard translated the scales into English and used them to assess intellectual functioning in institutionalized patients. In 1916, Lewis Terman published an Engligh-language version of

Binet's scaled named the Stanford-Binet. The first large-scale movement toward standardized testing came with the beginning of World War I and the need to properly select and assign new recruits. Goddard and Terman developed a test that relied on a deviation IQ in which an individual's performance was scaled by comparison with the performance of the cohort of individuals taking the exam (Yerkes, 1921). Test scores were converted to a scale in which the mean was arbitrarily set at 100 and the standard deviation was 15. In the 1930s, group tests of mental ability were developed and widely administered in the U.S. public school system. The development of tests for college admission derived from the work of Brigman at Princeton in the 1920s (Downey, 1961). This work eventually led to the development of the Scholastic Aptitude Test (SAT) in 1937.

Modern IQ scales began with the Wechsler-Bellevue test in 1939 (Wechsler, 1939) and the Wechsler Intelligence Scale for Children (WISC: Wechsler, 1949). In 1981, Wechsler developed an updated scale meant for normally functioning adults named the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler, 1981). Wechsler's tests have now become the gold standard in the field of psychometrics. Not surprisingly, new adult measures of mental ability are generally deemed unacceptable if their scores do not correlate with WAIS-R scores (Jackson, 1984).

The structure of mental ability. Beginning in 1904, there has been substantial disagreement on the structure of mental ability. The debate centres on a conflict between theories supporting a single unitary form of mental ability, and theories advocating multiple types of abilities.

Spearman's Theory. Spearman (1904) obtained correlations among several measures of sensory-discrimination ability. He noted that the correlations were positive and that discrimination ability could be assessed by an aggregate index. He related sensory-discrimination ability measures to measures of academic achievement and noted that these latter measures were positively correlated with each other and were positively correlated with his measures of sensory discrimination. Spearman assumed that there must be a common intellectual ability that accounted for the positive manifold of correlations, and labeled this ability factor "g" for "general mental ability". His two-factor theory assumed that the variance on a particular measure could be partitioned into a component attributable to g, which accounted for 74% of the common variance, and to a second specific source of variance that he named "s."

Thurstone's Theory. Thurstone (1931, 1938) developed the method of multiple factor analysis to evaluate independent factors present in a matrix of correlations. Thurstone's choice of factors was guided by the criterion of "simple structure" that mandated a structure in which tests loaded on a single factor and had a near-zero loading on other factors. Not surprisingly, results from Thurstone's analysis led him to advocate the existence of several independent primary ability factors. As a result, Thurstone's results placed him at odds with the results in Spearman's analysis. Luckily, later analyses would resolve this impasse through the development of a hierarchical factor structure.

Guilford's Theory. In the 1970s, Guilford (1977) developed a model of mental ability based on a three dimensional taxonomy that allowed him to classify any test or test items with respect to its position on the dimensions of operation, product and content. Overall, Guilford's model was comprised of 120 separate abilities that were based on a large set of factor analyses that Guilford claimed resulted in the identification of many of the factors that were postulated in his theory. However, it should be noted that Guilford's results do not support his theory, and there is ample evidence that many of his factors are significantly related. Therefore, in the absence of empirical confirmation, this theory cannot be construed as an acceptable alternative to a hierarchical model that retains a g factor (Brody, 1992).

Cattell's Theory. Cattell (1963, 1971, 1987) developed a theory of mental ability based on the distinction between two different g components: fluid mental ability (gf) and crystallized mental ability (gc). Fluid mental ability was viewed as a biologically influenced dimension of g, while crystallized mental ability was influenced by education and cultural exposures. The factors gc and gf were oblique, and often correlated in excess of .50.

Gardner's Theory of Multiple Intelligence. Gardner's theory (1983) is only mentioned here because of its widespread acceptance by the general public. Gardner's theory is based on seven "types" of mental ability (linguistic, logical-mathematical, spatial, musical, bodily, intrapersonal, and interpersonal) which were not derived through the factor analysis of psychometric tests, but rather, were identified in terms of several kinds of categorical data[1]. Both Brody (1992) and Jensen (1998) find Gardner's taxonomy to be arbitrary and without empirical foundations. Gardner's rejection of a superordinate g factor and his specific "types" of mental ability do not appear to have a firm theoretical or empirical basis.

Carroll's Theory. The most comprehensive analysis of the structure of ability factors was conducted by Carroll (1993). Carroll reanalyzed the canon of ability matrices (over 460 matrices) and developed a three-stratum taxonomic structure in which g exists as the singular third-order stratum at the apex of a hierarchical structure of abilities. Carroll's theory provides a useful means of reconciling the divergent theories advocating a unified (e.g., Spearman) or diversified (e.g. Thurstone) factor structure.

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[1] Categorical data includes the extent to which an ability can be impaired or preserved in isolation of brain damage, the existence of "idiot savants," and prodigies, along with "evolutionary plausibility."

Carroll portrays the structure of mental ability as a pyramid. The top of the pyramid, Stratum III, is the conceptual equivalent of Spearman's g. The middle of the pyramid, Stratum II, consists of eight factors (i.e. fluid mental ability, crystallized mental ability, general memory, broad visual perception, broad auditory perception, broad retrieval ability, broad cognitive speediness, and processing speed) that are differentially influenced by g. These abilities represent enduring characteristics of individuals that can influence their performance in a given domain. The abilities are also rank ordered with respect to their g loadings. It is interesting to note that these mid-level abilities all have a speeded component. For example, fluid mental ability is influenced by speed of reasoning, whereas crystallized mental ability is influenced by reading speed.

Summary and conclusion. There is convincing evidence that psychometric methods are a valid and reliable means of assessing individual differences in mental abilities. The discovery of g, the development of IQ tests, and various structural theories of mental ability have advanced our understanding on this topic. However, the contribution of psychometrics is limited to the descriptive domain. That is, IQ tests can tell us if a person possesses higher or lower levels of mental ability, and studies on the factor structure can tell us if IQ scores are due to a single or multiple factors. Unfortunately, a limitation to these studies is that they do not illuminate the underlying reasons behind these individual differences. The answers lie in the application of experimental psychology paradigms.

Elementary Cognitive Tasks

One of the oldest tenets in the study of mental ability is the notion that mental ability and sensory perception are closely related. This is hardly a new concept. In the late 1800s, Sir

Francis Galton attempted to relate mental ability to various measures of sensory acuity. Galton claimed that as information from the outside world must pass via the senses, enhanced sensory acuity can lead to a larger field upon which our "judgment and mental ability can act (Galton, 1883, p.19)." Because of a series of methodological difficulties, Galton's work was largely unsuccessful. However, beginning with a study by Jensen and Munro (1979), there has been a renewed interest in the study of individual differences in mental ability using information processing paradigms and models.

Information processing. Beginning in the 1950s, Eysenck (1952, 1967, 1976) forcefully implored differential psychologists to adopt the models and methods of experimental psychology in an attempt to understand the nature of individual differences. Eysenck maintained that a descriptive structure of mental ability is insufficient to claim paradigmatic status in the absence of a theoretical basis to endorse the taxonomy (Stelmack, 1997).

These statements were echoed by Jensen (1985) who asserted that the study of mental ability using psychometric measures alone was a "theoretical blind alley". He stated that the traditional methodology of studying mental ability in terms of classical psychometrics, factor analysis, and external validation has not contributed to the further development of theoretical explanations of the main abilities identified by psychometric tests. In experimental settings, the measurement and methods of psychometry reveal only the end products of mental activity, and, by themselves, cannot expose the processes between problem presentations and a participant's response.

One widely-used experimental method involved the application of information processing theory. Information processes are hypothetical constructs used to describe how a person apprehends, discriminates, selects, and attends to certain aspects of the vast range of stimuli that impinge on the various sensory systems to form internal representations. These internal representations can be stored in memory and later retrieved from storage to govern a person's decisions and behaviours (Jensen, 1998).

A technical definition of information processing involves uncertainty reduction. Information processing is used to describe a process that depends on the structural and physiological properties of the brain that are activated when uncertainly is perceived. The process involves reducing this uncertainty in an expeditious manner. There are two central tenets that apply to all information processing theories: 1) information processing occurs in stages, and 2) information processing occurs in real time, with each step in the process taking a certain amount of time (Jensen, 1998).

Elementary Cognitive Tasks. During the past 25 years, a relatively large number of researchers began to pursue a theory-driven search for basic elementary processes that underlie individual differences in mental ability. In order to isolate these basic processes, elementary cognitive tasks (ECTs) were developed. Elementary processes are defined as simple information processing skills (Brody, 1992) such as a behavioural reaction to a simple punctate stimuli. Elementary cognitive tasks are therefore tests that are simple and lack any specific skill or knowledge content. Despite this simplicity, ECTs are a useful analytic tool that reveal individual differences in performance. ECTs are made especially simple so that every participant in the study can easily understand and perform the task. The main source of individual differences on ECTs is not necessarily the correctness of the participant's response, but rather, response time – the time taken to complete the ECT (Jensen, 1998).

Elementary Cognitive Tasks in Children. Evidence of early ontological development of basic cognitive components related to mental ability derives from studies relating infant measures of sensory acuity to later IQ. These measures appear to involve some of the same basic cognitive abilities that characterize later mental ability, including speed of encoding, the storage and retrieval of information, discrimination, and recognition.

Using indexes of infant mental functioning such as visual recognition memory, habituation, cross-modal transfer, object permanence and attention, McCall and Carriger (1993) found significant relations between infant cognition and later mental ability. A study by Rose and Feldman (1995) extended these results. Two infant measures, a 7-month assessment of visual recognition memory and a 1-year assessment of tactual-visual cross-modal transfer predicted IQ at 11 years; correlating .41 and .24 respectively with full scale WISC-R IQ scores. Furthermore, a measure of perceptual speed at 11 years of age also correlated with these infancy measures.

The prediction of IQ over such a lengthy time interval (over 10 years), spanning a period of marked growth and development, supports the notion that some cognitive abilities assessed in later childhood are present, at least in rudimentary form, in infancy. Taken together, these results point to processing speed as a common factor underlying cognitive continuity from infancy. These results also support earlier speculations (see Colombo, 1993; Rose, 1989) that speed of processing is a pervasive factor underlying individual and developmental differences in many aspects of cognition, both in infancy and in older children.

The speed hypothesis. In the following section, the literature that links speed of information processing to individual differences in mental ability is reviewed. Although there are dozens of paradigms that have been used in this investigation, we will limit our discussion to the three most common tasks: response time, the Sternberg Paradigm, and the Posner Paradigm.

Response Time (RT)

The application of elementary cognitive tasks to the study of mental ability began in earnest with a study by Jensen and Munro (1979) published in *Intelligence*. Jensen (1982) considered the RT-IQ relation to be very important because the correlation between the two was evidence that mental ability was not just related to knowledge and skills. RT research offers a theoretical avenue for understanding differences in mental ability that is unavailable to differential psychologists who rely exclusively on psychometric methods.

Simple response time (SRT). In an SRT task, the participant depresses a telegraph key with the index finger. After a preparatory signal, an imperative stimulus to respond is presented. The RT stimulus can be either visual or auditory. The participant's task is to release the key as quickly as possible when the RT stimulus is detected. SRT is comprised of 1) sensory lag and stimulus transduction from the sense organ through the afferent nerve fibres to the brain, 2) effector time comprising the efferent nerve impulse from the brain to the muscles, and 3) muscle lag (Jensen, 1998).

Discrimination response time (DRT). In this task, the participant is confronted with the possible occurrence of two (or more) different reaction stimuli. The participant is instructed to respond to only one stimuli. DRT consists of all the processing components of the SRT, plus the additional time required to perform the discrimination (Jensen, 1998).

Choice response time (CRT). A CRT task includes both stimulus discrimination and making a choice between two (or more) different response alternatives, each keyed to a different reaction stimulus. Having to make a choice in responding to reaction stimulus is another cognitive process that adds to the total time over and above pure discrimination (Jensen, 1998).

Jensen (1998) provides a summary of the results from the vast number of RT-IQ studies. Overall, each type of RT task correlates negatively with psychometric IQ, meaning that individuals with higher IQ have shorter RTs. The correlations tend to be small, but increase in size, going from SRT (r=-.10) to DRT (r=-.20) to CRT(r=-.30). In general, these results replicate the well-established finding that individual differences in mental ability are more highly correlated with performance measures when the ECT is more complex.

One limitation to these RT-IQ studies is that they tend to employ participant pools comprised almost exclusively of university students. These samples tend to be demographically homogenous and possess a restricted IQ range. In an effort to extend these RT-IQ effects to the general population, Deary, Der, and Ford (2001) examined a sample of 900 55-year old participants with equal numbers of men and women, and closely related to the population as a whole in terms of social characteristics in Scotland. RT-IQ correlations tended to be somewhat higher, with SRT and CRT correlating -.31 and -.49 respectively. Separating the sample into subgroups by gender, educational level, social class, or number of errors on the RT task had no significant effect on the correlations. The authors believed that the larger effect sizes were due to a larger range of IQ scores in the participant pool.

Although there is some debate on the exact nature of the speed measure (e.g., speed of information processing, speed of semantic processing, speed of memory scanning), there is little argument that these consistent RT-IQ correlations support the notion that processing speed contributes to individual differences in mental ability.

Sternberg Paradigm

The Sternberg Paradigm measures the time taken to scan short-term memory for a particular item of information (Sternberg, 1966, 1969). In a typical Sternberg task, a trial begins with the participant depressing a home button. After a preparatory signal, a set of 1 to 7 digits appears simultaneously on the display for 3 seconds. The participant's task is to memorize the set of numbers. The screen then goes blank for 1 second and a single probe digit appears. The participant's task is to immediately answer YES or NO whether the probe was, or was not, present in the previously displayed set.

In general, RT increases with set size and it takes longer to answer NO than YES. The correlations between median RT and IQ are generally in the -.30 range (Jensen, 1987), indicating that speed of visual scanning is related to mental ability.

Posner Paradigm

The Posner Paradigm measures the speed of accessing long-term memory (LTM) for simple, highly learned items of information. This task is based on a contrast between two reaction time measures: 1) retrieval of information from long-term memory (LTM; name identity (NI) task), and 2) reaction time to a stimulus that does not require memory retrieval (physical identity (PI) task). In the PI task, a pair of letters appears on a computer screen. The participant responds on a binary console, pressing the SAME button if the two letters are physically identical (i.e. AA) and pressing the DIFFERENT button if the letters are not physically identical (i.e. Aa). In the NI task, the same letter pairs are presented, but now the participant is instructed to respond according to the name identity or nonidentity of the two letters (i.e., Aa = same, Ab = different). The difference between the median RT to the NI task and the median RT to the PI task can be used to assess the time required to access the letter names in LTM (Jensen, 1998). Overall, this measure of LTM correlates with full-scale IQ in the -.35 level (e.g., Vernon, 1983) indicating that participants with higher IQ scores take significantly less time accessing information in LTM.

Implications

Overall, these speed results (notably RT) the Sternberg Task, and the Posner Paradigm, clearly indicate that individual differences in mental ability are influenced by speed of information processing. These speed of processing tests have very little surface content in common with psychometric IQ tests. Consequently, these results are contrary to the notion that IQ tests simply measure the knowledge that an individual has amassed, the problem-solving strategies that he/she has developed, and the opportunities that he/she has had to learn (Vernon, 1983). One of the limitations to these studies is that there is no clear and unambiguous theory that can explain the observed relation between speed and IQ. However, there are a few predominantly held views.

Vernon (1983) views these speed of processing tests as measures of a person's efficiency in performing very basic cognitive operations. These cognitive operations are carried out in a short-term memory (STM) system, characterized by a limited capacity to hold information, rapid decay or loss of information in the absence of rehearsal, and encompass a trade-off between the amount of information that can be held and processed simultaneously. Speed or efficiency with which individuals can perform these cognitive operations can have a considerable effect on the success in their performance on a task. Vernon (1983) therefore contends that cognitive operations, such as encoding, STM processing, and LTM retrieval, are integral components in all forms of intellectual behaviour.

The sensory discrimination hypothesis. Another body of literature suggests that sensory discrimination rather than speed related to mental ability. In 1904, Spearman found that pitch discrimination correlated with various measures of general mental ability in the range of .41 to

.72 after correction for attenuation. Since that time, a number of studies have confirmed Spearman's findings.

Two notable studies have found that IQ is related to the strength of certain optical illusions. Holt and Matson (1974) reported that IQ and age both significantly affected the number of reversals on a Necker cube in a sample of 50 school-aged children. These findings were replicated by Beer, Markley and Camp (1989). Wechsler Adult Intelligence Scale (WAIS) scores were positively correlated with Necker cube reversals (.38), Shroeder staircase reversals (.37), Mach book reversals (.46), and the detection of embedded figures (.75). The fact that higher IQ participants are more susceptible to visual illusions than lower IQ participants can be explained by the fact that these illusions are the result of a greater amount of mental transformation of a stimulus (Beer et al., 1989).

Lynn, Wilson and Gault (1989) presented a series of simple musical tests involving accuracy rather than speed to a group of 9-10 year old children. Results from this study provided clear evidence that performance on simple musical tests is related to psychometric IQ. Since the musical tests were unfamiliar to the children, individual differences were unlikely to be due to different opportunities for learning, which were themselves a function of social class, education, and family environment. The tests appear to measure the efficiency in which the musical information is transmitted by the auditory tract and accurately analyzed by the brain.

An interesting feature of these visual and auditory studies is that these tests solely measure accuracy and not speed. Nevertheless, there is evidence of a modest relation between IQ and sensory discrimination ability. Unlike RT tasks that contain a speeded behavioural component, it is difficult to explain these stimulus discrimination effects in terms of differences in efferent or motor speed. As a result, these stimulus discrimination effects can be understood in terms of individual differences in central information processing.

Inspection Time. The inspection time (IT) paradigm introduced by Nettelbeck and Lally (1976) differs radically from speeded RT tasks. Rather than manipulating information load, the time allowed for stimulus processing is manipulated. The threshold exposure time needed for correct identification of the target stimuli is called "inspection time" (Raz, Willerman, & Yama, 1987). IT has both peripheral and central processing components, but theoretically, only the central component correlates with IQ. The IT paradigm completely eliminates the efferent or motor part of the peripheral sensorimotor component. Although IT is less complex than most RT tasks, it generally has higher correlations with IQ. With the exception of sensory discrimination tasks, IT is the only index of cognitive processing that does not involve motor components or executive cognitive processes. IT is believed to measure individual differences in the "speed of apprehension," the quickness of the brain to react to external stimuli prior to any conscious thought (Jensen, 1998; Nettelbeck, 2003).

Both visual inspection time (VIT) and auditory inspection time (AIT) are good predictors of psychometric mental ability. VIT and AIT methodologies will be described separately, but results will be presented in a common section.

Visual Inspection Time (VIT)

In a typical VIT task, a participant is told to fixate on a target point in the centre of a display screen. After three seconds, a red dot appears and the test figure appears immediately in the centre of the screen. The test figure typically contains two vertical lines of unequal, but easily discernable, lengths. After an interval of t seconds, the masking figure appears in exactly the same location as the test figure, completely covering it. The purpose of the masking stimulus is to reduce the impact of higher-level cognitive strategies. The participant then indicates, with a button press, whether the longer line was on the left or the right side of the display. The participant can take as much time as is necessary to make the decision. The time interval between the appearance of the test figure and the masking figure varies systematically from trial to trial. The computer program controlling stimulus exposure is reactive and takes into account the participant's pattern of correct and incorrect responses on each trial. The program automatically makes the interval longer or shorter until it stabilizes at a point where the participants respond correctly on 75 %[2] of the trials (Nettelbeck, 2003)

Auditory Inspection Time (AIT)

Although there are various versions of the AIT task, the first AIT study, conducted by Brand and Deary in 1982, is typical. The auditory task consisted of two square wave tones of markedly different pitch played consecutively. The duration of the tones varied between 2.7 ms and 100.0 ms. The participant was asked to respond by stating the temporal order of the two tones (i.e., high-low, low-high). Both tones were forward and backward masked using white noise. This type of paradigm has been used by other researchers including Irwin (1984), Nettelbeck, Edwards and Vreugdenhil (1986), and Deary, Head, and Egan (1989).

Inspection Time Results

The first study examining the link between visual IT and IQ was conducted in 1976 by Nettelbeck and Lally (1976). The aim of this study was to test the idea that low IQs found in developmentally delayed individuals may reflect slow "mental speed". The application of the IT paradigm to a small sample (N=10) revealed an IQ-IT correlation of -.90. Although these

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[2] Historically, the accuracy criterion was 97.5%. Based on the results from a study by Levy (1992), the 75% criterion is now generally accepted.

correlations were spuriously inflated because of the inclusion of developmentally delayed participants, it nevertheless confirmed the feasibility of further IT-IQ studies.

Both visual inspection time and auditory inspection time show reliable individual differences that are substantially correlated with IQ throughout the full range of biologically normal mental ability. The most commonly cited meta-analysis linking inspection time with mental ability was conducted by Kranzler and Jensen (1989). They found that general IQ correlated (after correction) -.56 in a sample of 633 adults and -.59 in a sample of 242 children. One limitation to this meta-analysis, however, was that no distinction was made between auditory and visual studies. A more recent meta-analysis conducted by Grudnik and Kranzler (2001) replicated and extended Kranzler and Jensen's (1989) findings using a sample of 4200 participants in 92 studies. Across all studies, the corrected inspection time-IQ correlation was -.51 in adults and -.44 in children. When studies were categorized by stimulus modality, the VIT-IQ correlation was -.49 and the AIT-IQ was -.58. The relationship between IT and IQ seems to be strongest for measures of performance IQ and weakest for measures of verbal IQ, with the measures of general IQ in between.

Is the IT-IQ correlation due to speed or sensory discrimination?

There is currently some debate about the fundamental nature of the IT-IQ relation. Some researchers (e.g., Deary and Vernon) see IT as a measure of the speed of information processing and speed of sensory discrimination respectively, while others (e.g., Jensen) sees IT as a measure of sensory discrimination ability.

Although IT was originally believed to be an index of speed of processing, Irwin (1984) reported that children's AIT scores correlated -.51 with scores on the unspeeded Seashore pitch discrimination task. Raz et al. (1987) found correlations between -.42 and -.54 among measures of frequency resolution and IT in a sample of university students. This raises the possibility that the IT-IQ correlation is due to pitch discrimination ability. If the IT task is shown to be a measure of pitch discrimination, then the hypothesis that the IT-IQ correlations is mediated by speed of information processing loses much of its explanatory power.

A study by Deary et al. (1989) correlated AIT and IQ test scores while taking into account differences in performance on the Seashore pitch discrimination task. In this study, the Seashore-AIT correlation was not significant and the AIT-IQ correlation decreased very little when pitch discrimination was statistically partialled out in a sample of adult participants. This study was repeated with children. Pitch discrimination correlated .15 with IQ in this sample but the partial correlations between IQ and AIT, controlling for pitch discrimination, differed only minimally from the uncontrolled correlations. It appears, therefore, that while AIT correlates at low levels with pitch discrimination ability, the AIT-IQ correlation is due to temporal resolution speed rather than the ability to make fine pitch discriminations.

Although it appears that IT is a speeded measure, it is still unclear which type of speed is involved. Nettelbeck (2001) states that recent evidence does not support the claim that IT estimates the speed of a single mechanism like "sampling input" or "apprehension." Rather, IT appears to be sensitive to both the focused attentional capacities to detect organization and changes under severe time constraints, and to decision processes, ongoing beyond mask onset, that monitor responding.

Although the exact nature of the IT-IQ correlation is not clearly understood, 25 years of research have confirmed that IT taps low-level aspects of psychological processes that contribute to individual differences in mental ability. Whether this capacity is properly described by a single mechanism remains unclear.

Frequency Discrimination. A series of studies (Raz, Willerman, Ingmundson, & Hanlon, 1983; Raz & Willerman, 1985; Raz et al., 1987) applied an auditory discrimination task based on the work of Massaro (1970; 1972). The Raz Paradigm differs from the AIT tasks described above in two important ways. First, Raz's Paradigm involved a manipulation of the time between a target tone and a masking stimulus. Second, only single tones are presented and the participant's task is to identify a test stimulus as being "high" or "low" pitch, rather than identifying the "high-low; low-high" sequence in a pair of tones.

In the first experiment (Raz et al., 1983), an auditory backward recognition masking task was administered to a sample of 14 undergraduate students. Participants were asked to discriminate between higher (870 Hz, 20 ms duration) and lower (770 Hz, 20 ms duration) pitched tones that were followed by a masking tone (820 Hz, 500 ms duration). Mask onset varied between 0 ms and 1000 ms in thirteen conditions. Overall, higher ability participants performed reliably better than lower ability participants. Furthermore, performance for all participants increased during longer mask onset conditions. There was also an interaction between ability and mask onset, suggesting that participants from the higher ability group performed especially well in shorter mask onset (i.e., more difficult) conditions. These results indicate reliable information processing differences between the two ability groups on a task that does not require sophisticated reasoning.

In the second study (N=20; Raz & Willerman, 1985), the duration of the target tones varied between 20 ms and 30 ms, and mask onset varied between 0 ms and 250 ms in six conditions. Once again, higher ability participants performed much better than lower ability participants in all conditions. Furthermore, the higher ability group's performance was better during shorter mask onset conditions. The correlations between mental ability and auditory recognition threshold (the point where tone detection dropped below 75%) was -.73 for 30 ms tones and -.69 for 20 ms tones.

In a third study (Raz et al., 1987) conducted with a larger sample (N=36), tones of 10, 13 and 20 ms were followed by a masking stimulus that was presented at 0, 20, 30, 60, 120, and 480 ms. Much like study 2, the correlations between Cattell's IQ scores and auditory recognition threshold were -.47, -.44, and -.53 for 10, 13, and 20 ms tone durations respectively.

Although Raz's results were very promising, there were no large-scale replications of his paradigm. Attempts to adapt Raz's paradigm to studies using electrophysiological measures were largely unsuccessful due to recording software limitations (Bazana, personal communication).

The Role of the Masking Stimulus. A masking stimulus is frequently employed in many elementary cognitive tasks (ECTs) including the Sternberg and Inspection Time (IT) paradigms. There is no doubt that the masking stimulus limits processing of information from stored traces. If ECT paradigms, particularly the IT paradigm, did not use a masking stimulus, the task would be so easy that individual differences would not emerge except in very rare cases (White, 1993). The main assumption of the IT rationale is not merely that backward masking limits stimulus persistence, but that it experimentally determines the length of time that a stimulus representation is available for further processing.

There has been some disagreement, however, on the role of the masking stimulus. Despite the fact that many rival hypotheses have been proposed to account for the wealth of findings on masking, the majority of plausible explanations can be classified as either "interruption" or "integration" theories.

Interruption Theory

It the early 1960s, researchers observed that more elements could be reported from a backward masked multi-element display when there was a longer delay before the presentation of a mask (Averbach & Sperling, 1961; Sperling, 1963). For example, when the presentation of a display consisting of a row of randomly selected letters was immediately terminated by the presentation of a visual noise mask, Sperling (1963) found that there was a linear relation between the duration of the display and the number of letters correctly reported. As a result of these findings, Averbach and Sperling (1961) developed the interruption theory of backward masking.

The main assumptions of the interruption theory, highlighted in Averbach and Sperling (1961) are:

1. A visual information store exists which is capable of storing the full spatial details of up to about 100 items for a period of up to 250 ms.
2. The buffer takes in target information instantaneously.
3. The information is then immediately available to be "read out" for further processing.
4. The information is read out relatively slowly.
5. Read out time is terminated by the arrival at the buffer of the representation of the mask which completely overwrites the target, rendering it unavailable for further processing. The mask does not affect clarity – it only affects the duration for which the target is available to the buffer.

The interruption theory assumes that the target representation is available for further processing for the entire time period before the mask is presented, and that any delays in target processing caused by the backward mask must be due to limitations in the speed with which target information is read out of the buffer. The interpretation of the ECT-IQ relationship using an interruption framework is very straightforward and simple: higher ability individuals have faster speed of processing at the post-sensory level than lower ability individuals. Information can be transferred from the sensory buffer to short-term memory before stimulus processing is interrupted by the presentation of the mask.

While the interruption theory has had limited experimental support, most of the literature on pattern masking indicate that the integration theory provides an even better explanation of these findings. Integration theory is also able to explain a whole range of other findings that interruption theory cannot explain (White, 1993).

Integration Theory

The interruption theory of simple, backward pattern masking has now been replaced by the integration theory which explains masking in terms of a lack of fine temporal resolution in the sensory system, such that the target and mask are treated as through they were presented simultaneously (DiLollo, 1980, Eriksen, 1980). According to the integration theory, two patterns which are indistinguishable when presented simultaneously will also be indistinguishable when presented sequentially in close temporal proximity. However, at longer temporal proximities, the mask will no longer fully integrate with the target, and the separate target and mask patterns will be identifiable. Within this framework, a decision time construct such as IT is interpreted as a measure of the temporal resolution of the sensory processes that underlie pattern detection. The most important implication of the paradigm shift from interruption to integration theory is that the locus of the decision time delay is shifted from the post-sensory to the sensory level (White, 1993; 1996).

The predictions of the interruption theory differ from those of the integration theory in two major ways:

1. Interruption theory is an "all-or-none" theory. The mask completely erases or displaces the target. The physical characteristics of the mask are irrelevant. In contrast, the integration theory claims that stimulus degradation is a matter of degree.

2. Interruption theory assumes that only the second of the two stimuli can have a masking effect (backward masking), which integration theory makes no such assumption. Forward masking is possible in the integration theory framework.

The use of the integration theory when explaining ECT results has very clear implications. The conclusion that the processing delay is sensory in origin necessitates the reinterpretation of the ECT-IQ relationship. Notably, this ECT-IQ relationship is not mediated by common cognitive-level variables but, rather, by common underlying sensory mechanisms.

Summary and conclusion. Convincing evidence suggests that higher and lower ability individuals differ in their performance on a range of ECTs. However, there is still much debate about the mechanisms that can be used to explain these results. Although some studies were intentionally designed to examine the role of various cognitive/sensory constructs, many of these studies used an ad hoc approach to explain the observed mental ability group differences.

One obvious oversight is that the entire ECT literature presupposes a bottom-up approach where elementary cognitive components contribute to individual differences in mental ability. No attention is paid to top-down processes such as rule adherence, instructions, and training. Conceivably, these factors would contribute to task performance. For example, if a participant receives incomplete instructions, task performance could be negatively impacted. This is a top-down effect.

While there is little doubt that top-down processes do relate task performance on a group level, there is very little indication that differences in these top-down processes would contribute to individual task performance. The direct evidence for this is that the error rates in these elementary cognitive tasks are extraordinarily low (Jensen, 1998). Individual differences are usually attributed to response time and response variability. Furthermore, participants are generally excluded from a study if it is determined that they did not understand the instructions.

In most cases, participants are given practice trials and are not allowed to continue unless they master the task. It is, therefore, unlikely that individual differences in top-down processes would contribute to the strong mental ability effects present in the ECT literature. From a theoretical and practical standpoint, only these bottom-up processes are of interest to mental ability researchers.

In many cases, these ECT findings have been attributed to an underlying biological mechanism. For example, individual differences in RT have been attributed to nerve conduction velocity. In the next section, studies that have applied biological approach to the study of mental ability will be discussed. Although these studies are atheoretical, they nevertheless provide a basis for the development of a mental ability theory.

The Biology of Mental Ability

Mental ability was originally examined using psychometric and behavioural methods. However, it is important to determine if the findings extends to a broader biological and physiological realm. A demonstration of the biological nature of mental ability will not only prove that mental ability is more than a random collection of learned facts and strategies, but also that it is related to something beyond the purely psychological or behavioural. A correlation between psychometric indices of mental ability and physical variables indicates that mental ability is connected to underlying biological systems (Jensen, 1998). Biological factors such as head size, nerve conduction velocity, and brain energy usage will be briefly reviewed. The majority of the information presented in this section pertains to event-related potential examinations of individual differences in mental ability.

Head Size and Brain Volume. A meta-analysis of 54 studies (from 1906 until 1999; N=56,793) indicates that the head size-IQ correlation is .19 (Vernon, Wickett, Bazana, & Stelmack, 1999). Once these studies are corrected for the unreliability of the IQ test and for restriction of range, the correlation increases to .20. A noteworthy finding is that not one single study showed a negative or nil relation between head size and IQ.

With the advent of computerized tomography (CT) and magnetic resonance imaging (MRI) technology, it is possible to obtain in vivo estimates of brain volume. A meta-analysis of 14 studies (N=858) reveals a brain volume-IQ correlation of .37 (Gignac, Vernon, & Wickett, 2003). This correlation increases to .50 when correcting for the unreliability of the IQ measure and restriction of range. There are no significant left-right asymmetry effects (Wickett,Vernon, & Lee, 2000). Brain volume was predictive of general mental ability and fluid mental ability, but not crystallized mental ability. Furthermore, correlations with small regions (i.e., caudate) tended to be small whereas correlations with larger areas (i.e., frontal lobe) tend to be moderate. The largest correlations are found with full brain volume.

Nerve Conduction Velocity (NCV). NCV refers to the speed at which electrical impulses are transmitted along nerve fibers and across synapses (Reed & Jensen, 1991). NCV can be measured peripherally using the median nerve of the arm, or centrally using known visual and auditory pathways.

Peripheral nerve conduction velocity (pNCV) is based on the assumption that the properties of neural tissues that are associated with NCV may be more or less similar in all nerve cells, both centrally and peripherally (Jensen, 1998). Although a meta-analysis of 12 studies (N=922) shows a mean correlation of .18 between pNCV and IQ (Vernon, et al., 1999), results were mixed with some studies showing a strong positive association (Vernon & Mori,1992), some showing no association (Reed & Jensen,1991) and others finding strong negative associations (Tan, 1996).

In a review of these findings, Jensen (1998) speculates that these inconsistent results are in fact due to several important methodological differences. These methodological differences include differences in pNCV recording parameters and in the gender composition of the participant pool. Some studies contained mixed gender samples while others employed only female participants. In an effort to examine the role of gender, Tan (1996) found that the pNCV-IQ correlations were .63 for men and -.55 for women, leading these researchers to speculate that this relation may be mediated by testosterone. It is also likely that the underlying assumption that the properties of neural tissues in the periphery generalize to the brain is unfounded. Clearly, the relation between pNCV and mental ability remains a puzzle and can only be resolved by further research.

More direct measures of NCV in the central nervous system were developed (cNCV). Reed and Jensen (1991) studied the relation between IQ and nerve conduction velocity in the visual pathway. The visual system was activated using a checkerboard pattern reversal design. The latency of the P100 (i.e., a visually evoked potential recorded over the primary visual cortex) was used to estimate cNCV in the visual pathway. An estimate of the length of the visual tract using head length was divided by the time between the pattern reversal and the activation of the primary visual cortex. After correcting for restriction of range, the IQ-cNCV correlation was .37.

Central NCV has also been studied in the auditory pathway. Stelmack, Knott, and Beauchamp (2003) employed brain stem auditory evoked potentials (BAEPs) to estimate auditory cNCV. BAEPs are a result of the activation which occurs from the auditory nerve, to the pons, to the inferior colliculus. The length of the auditory tract (distance) was estimated by calculating the cubic root of the approximate brain size (using multiple head measures) as outlined in Schmidt-Nielsen (1975). Overall, low positive correlations between BAEP latencies and IQ were observed indicating slower speed of processing for individuals with higher IQ (Stelmack, et al., 2003). These data contradict a speed-IQ hypothesis. However, the authors urge caution and recommend a replication before strong conclusions can be drawn from this study.

Cerebral Glucose Metabolism Rate. Cerebral Glucose Metabolism Rate (CGMR) is measured through positron emission tomography (PET). PET allows a detailed, direct and noninvasive determination of cortical and subcortical glucose metabolic rate. PET can thus determine which brain areas are metabolically activated during specific task performance or stimulus perception.

In a number of studies using CGMR, PET was used while participants completed a cognitive task. Overall, performance on IQ tests show significant negative correlations with CGMR. Haier et al. (1988) reported a correlation of -.84 between CGMR and performance on the Raven's Advanced Matrices Test. Parks et al. (1988) reported a correlation of -.50 between CGMR and scores on a verbal fluency test, and -.58 with scores on the Wechsler Adult Mental ability Scale – Revised. Lower IQ participants may have inefficient neural circuitry which may be due to the use of more energy by each neuron and/or the use of more neurons to perform the task. Higher IQ participants either have more efficient neural circuits in general, or access the circuit with a minimum amount of energy.

Event-Related Potentials

There is a growing body of research using event-related potential (ERP) measures that has explored individual differences in mental ability from an information processing perspective. ERP recording procedures provide indices of cognitive processes that complement and clarify the effects observed with behavioural measures. These procedures do show some promise to explicate the relation between mental ability and speed of cognitive information processing.

Event-related potentials (ERPs) are derived from electrical activity of the brain that is recorded using electrodes placed on the scalp. ERP waveforms are obtained by averaging ongoing electroencephalogram (EEG) activity that is time locked to a specific stimulus event. These waveforms develop in response to repeated presentation of specific stimuli, such as tones or light flashes, or during such cognitive processes as recognition, decision-making, and memory for specific stimulus events. It is assumed that random EEG activity emanating from neural sites that are not engaged in the repeated presentation of the stimulus is canceled out in the averaging process. What remains is a signature of the neural activity that occurred during the processing of that stimulus. These ERP waveforms consist of a series of positive and negative waves, or components of the waveform, that are designated by their polarity (positive or negative) and latency (in ms). For example, a negative wave that develops at 200 ms is designated as N200; a positive wave that develops at 300 ms is designated as P300. Physical characteristics of the stimuli (e.g., intensity and frequency), and cognitive processes (e.g., attention, decision-making, and semantic expectancy), influence the latency and amplitude of the ERP waves.

It is common practice to distinguish between exogenous and endogenous components of the ERP waveform that are primarily influenced by sensory and cognitive processes respectively. The exogenous sensory components are distinct, reliable waveforms that occur within 100-200 ms following the repeated presentation of simple tones, light flashes or visual grating pattern reversals (Harter & White, 1970). These waves are primarily affected by the physical characteristics of the stimuli. The neural generators of these waves are based in the primary sensory cortex and association areas of the brain (e.g., Chiappa, 1990). The endogenous cognitive components are relatively independent of the physical characteristics of the stimulation. These waves are sensitive to variation in the processing demands of cognitive tasks such as detecting novel stimulus change, stimulus classification, and categorization. The neural generators of these endogenous waves are complex and not well understood at this time. There is some agreement, however, that both the medial temporal lobe (Knight, Scabini, Woods, & Clayworth, 1989), and the hippocampus are involved in the generation of the P300 wave (McCarthy, Wood, Williamson, & Spencer, 1989).

Background

Much of the early research on mental ability employing ERP procedures focused on the exogenous, sensory components that were derived from the repeated presentation of light flashes or tones. This work was guided by the hypothesis that higher mental ability is characterized by faster neural transmission or greater neural efficiency (e.g., Ertl & Schafer, 1969). Faster reaction time for individuals with higher mental ability is a well-established and reliable effect that was demonstrated on a wide range of elementary cognitive tasks (ECTs). However, there is little support for the speed of neural transmission hypothesis from ERP work that examined exogenous, sensory ERPs to the repetitive presentation of tones or light flashes. This work was reviewed in detail by Deary and Caryl (1997) and by Stelmack and Houlihan (1995). These reviews found no reliable relation between mental ability and the latency of exogenous ERP waves to simple repetitive sensory stimulation. Moreover, the variation of mental ability with the amplitude of these waves in the 100-200 ms range is not consistently observed. Unfortunately, the more rigorous the study, the more likely is it that the study reports no reliable effects (Barrett & Eysenck, 1992; Davis, 1971; Vogel, Kruger, Schalt, Schnobel, & Hassling, 1987).

Recently, the pattern reversal paradigm was employed by Burns, Nettlebeck and Cooper (2000) to examine individual differences in mental ability. The sample was composed of 38 male and 26 female participants, who ranged in age from 18 to 42 years (mean age was 26 years). The pattern reversal stimuli and procedure were very similar to that of Reed and Jensen (1992) including bipolar recording between midline central and midline occipital recording sites. The mental ability measures consisted of several tests from the Woodcock-Johnson Psycho-Educational Battery-Revised (Woodcock & Johnson, 1989) that were markers for fluid ability, crystallized ability, short-term memory, visual processing, and speed of processing. From this selection, a cross out test marking speed of processing, displayed a negative correlation ($r = -.21$) with the P100 wave. Overall, there is some evidence, at this time, of a modest negative correlation of mental ability with the P100 wave derived from the pattern reversal paradigm, but more work with this procedure is required before it is acknowledged as an established effect.

It is important to consider the functional significance of these exogenous ERP waves and whether these functions converge with performance on psychophysical or behavioural tasks that vary with psychometric mental ability measures. This would be helpful in explicating the nature of psychological processes that are relevant to mental ability. Exogenous ERP waves are primarily measures of the speed (i.e., latency) and strength (i.e., amplitude) of reaction to simple physical stimuli. Functionally, these measures are especially sensitive to variation in the intensity of stimulation, showing shorter latency and larger amplitude with increase in intensity of stimulation. To our knowledge, however, there are no studies that report an association between psychometric mental ability and psychophysical measures of reaction to stimulus intensity (i.e., absolute sensory thresholds, pain thresholds, noise thresholds, or sensory magnitude estimations). Thus, there is no convergence of mental ability and the effects to which exogenous

ERP measures are functionally related. To a great extent, this lack of convergence pre-empts an association between mental ability and the exogenous ERP waves.

Further to this issue, it is also important to consider that studies of the association between mental ability and performance on simple sensory tasks, beginning with Spearman in 1904, invariably required determining relations between stimuli (i.e. size, weight, tonal frequency, and light intensity discrimination thresholds), rather than reactions to punctate physical stimulation (e.g. absolute thresholds, direct magnitude estimations). In the more recent work, comparative judgments were also a feature of many of the elementary cognitive tasks that demonstrate a relation between mental ability and speed of information processing. From this perspective, it would be worthwhile to pursue the examination of these discrimination effects using ERP measures whose functional significance do converge with information processing tasks that are related to measures of mental ability. An endogenous ERP wave with positive polarity that develops maximum peak amplitude at about 300 ms on simple discrimination tasks (i.e., P300) is established as a reliable index of the speed and effort exhibited during the performance of several cognitive tasks.

P300 as an index of information processing

The P300 is a positive component of the ERP wave that develops maximum peak amplitude at central and parietal electrode sites approximately 300 to 800 milliseconds after the onset of a novel or task-relevant stimulus (e.g., Picton, 1992). The amplitude of the P300 varies inversely with the subjective probability of occurrence of a target stimulus. For example, in a widely studied procedure, termed "the oddball paradigm", rare or infrequently occurring stimuli presented in a series of more frequently occurring standard stimuli, elicit a larger amplitude P300 wave than the standard stimuli (e.g., Polich, 1987). The amplitude of the P300 wave also varies directly with increases in stimulus complexity, task complexity, and stimulus value (Johnson, 1988). These factors are thought to demand an increase in perceptual processing resources that are reflected in an increase in P300 amplitude. The P300 wave is also influenced by factors that affect the transmission of information. Specifically, P300 amplitude varies inversely with conditions that increase task difficulty such as degrading the stimulus and decreasing stimulus exposure time. Thus, P300 amplitude is a measure that can be usefully employed to examine the extent to which individual differences in perceptual processing resources, and in efficacy of information transmission, can contribute to variation in mental ability.

The latency of the P300 wave is a useful index of the time required for stimulus evaluation and classification. It is well established that the latency of the P300 wave increases with increases in perceptual processing demands and in task difficulty (Johnson, 1988). An important feature of this component is that P300 latency is relatively independent of response selection and execution processes, yielding a discrete measure of cognitive processing speed (Polich, 1987). The independence of P300 latency and response production processes was demonstrated in several studies where emphasis on instructions to respond accurately or as fast as possible affected reaction time but not P300 latency. For example, in a task that manipulated speed and accuracy instructions as well as semantic categorization difficulty, both P300 latency and response time increased with increased cognitive task demands imposed by increasing categorization difficulty. The speeded instructions decreased response times, but had no effect on P300 latency (Kutas, McCarthy, & Donchin, 1977). In effect, P300 latency was sensitive to the cognitive task demands but not to the response production demands. These effects were also demonstrated in several stimulus-response compatibility paradigms in which incompatible stimuli (i.e., word/colour, cue/direction), increased both response time and P300 latency, but incompatible responses only increased response times, not P300 latency (e.g. Doucet & Stelmack, 1999; Duncan-Johnson & Koppel, 1981; Houlihan, Campbell, & Stelmack, 1994). The independence of P300 latency from response execution makes the P300 latency measure a useful adjunct to reaction time measures in chronometric studies of information processing speed.

Mental ability and P300 latency and amplitude during the oddball paradigm

Several investigators examined the relation between mental ability and P300 amplitude and latency using an auditory oddball paradigm. In the studies cited here, healthy adult participants were presented with infrequently occurring tones that differed appreciably in tonal frequency or intensity from more frequently occurring standard tones. A significant negative relation between P300 latency to the infrequently occurring (deviant) tones and measures of mental ability was observed with good consistency. This effect was evident at different levels of attention, including passive conditions (e.g., where the participant was instructed to ignore the tones), and active conditions (e.g., where the participant was instructed to count the infrequently occurring tones or to press a button when a deviant tone was detected).

An auditory oddball paradigm was used by Polich, Howard, and Starr (1985) to assess the relation of the P300 wave to mental ability. Infrequently occurring tones, with a tonal frequency of 2000 Hz and having a probability of occurrence of 20%, were presented among a series of 1000 Hz standard tones. The sample, comprising 96 male participants ranging in age from 5 to 87 years, was substantial. A negative correlation (-0.40) was observed between digit span performance and the latency of the P300 wave. In a subsequent study (Polich & Martin, 1992), the same oddball paradigm was employed but in addition, the frequency of occurrence of the target tone was presented at 50 % and at 80% probability of occurrence. Moreover, a battery of ability measures was administered, including grade point average, digit span, digit symbol and

Raven matrices. The sample was composed of 54 participants (27 males and 27 females). A negative correlation between grade point average and P300 latency was reported, but no other significant effects were observed. The absence of a strong P300 latency-IQ effect is possibly due to methodological differences. In some of the conditions employed by Polich & Martin (1992), the target tone was presented at a 50% probability of occurrence. Johnson (1988) would argue that this frequency of occurrence renders the target tone an equiprobable event that no longer meets the definition of a deviant tone. In fact, Johnson's triarchic model predicts that P300 decreases systematically as the probability of a target tone increases. It is possible that the P300 generated in these conditions was not large enough to be reliably measure, thus attenuating the results.

The association of higher mental ability with shorter P300 latency in an auditory oddball paradigm was also reported for both active and passive conditions (O'Donnell, Friedman, Swearer, & Drachman, 1992). In the active condition, participants (14 men and 27 women) counted a 1500 Hz target tone that occurred with a 10% probability of occurrence among a series of 1000 Hz standard tones. In the passive condition, the participants were told to ignore the tones. In this condition, the deviant tones were low frequency (250 Hz), low intensity (70 dB) tones that were presented with a 30% probability of occurrence among a series of high frequency (3000 Hz), higher intensity (85 dB) tones. P300 latency scores were negatively correlated with factor scores for verbal learning (-0.32) and verbal fluency (-0.39) in the passive condition, and with crystallized mental ability (-0.44) and concentration (-0.33) in the counting condition. A significant problem with this study was that stimulus characteristics varied substantially between active and passive conditions. In the active condition, the target stimuli had a frequency of 1500 Hz with a 10% probability of occurrence. In the passive condition, target tones had a frequency of 250 Hz with a 30% probability of occurrence. Furthermore, the relative difference between standard-target tones in the active condition was 500 Hz and was 2750 Hz in the passive condition. Because of these difficulties, it is impossible to determine if the observed attentional differences were due to stimulus characteristics or from attention level. This is why the vast majority of studies that employ active and passive conditions use identical stimulus characteristics.

A broad range of mental ability measures were also employed in an ERP study reported by Egan, Chiswick, Santosh, Naidu, Rimmington and Best (1994). Again, the auditory oddball paradigm was used. In this case, the stimuli were short duration tone-pips. The target stimuli had a frequency of 1500 Hz with a 10% probability of occurrence and the standard stimuli had a frequency 1000 Hz. The sample was composed of 48 men and 2 women. They found significant correlations between P300 latency and digit symbol (-.30), digit span (-.29), auditory verbal learning (-.25), two trail making tasks (.27 and .41), and word fluency (-.29). A significant relation was also found between P300 amplitude and the similarities and arithmetic subscales of the Wechsler Adult Intelligence Scale (WAIS), as well as verbal mental ability (-.35), logical memory delay (-.31), auditory verbal learning (-.41), and a trail-making test (.28).

Despite some reservations concerning the selection of participants, the outcome of studies that examined the relation of mental ability and the P300 wave using the auditory oddball paradigm show some consistency. All studies cited do report a significant correlation between mental ability measures and P300 latency to the deviant tone in the oddball paradigm, linking higher ability to faster latency of detection. The digit span test, a widely employed measure of short-term memory, appears to be the mental ability measure most frequently observed to exhibit a significant negative relation with P300 latency. All of the studies cited were conducted with sample sizes that were sufficiently large so as to counter sampling bias. On the other hand, the confound of age (Polich, et al. 1985) and gender (Polich & Martin, 1992; O'Donnell et al., 1992) do have the potential to bias the effects that were reported. Both age (Polich, 1996) and gender (Cahill & Polich, 1992) do have differential effects on the P300 wave.

In assessing the relation of mental ability and the P300 wave obtained during the oddball paradigm, P300 amplitude effects were notably absent. This could be due to the low level of the perceptual processing demands that were required. The level of task difficulty was very easy in these auditory oddball paradigms because the difference in tonal frequency between the target and standard tones was quite large. An exception here is amplitude effects observed by Egan et al. (1994). In that case, short duration tone pips were employed that could make the discrimination of target from standard tones more difficult resulting in greater variation in P300 amplitude.

Mental ability, elementary cognitive tasks and P300 latency and amplitude

Several authors have examined the relation between mental ability and the P300 wave that develops during the performance of the Sternberg task to either, or both, the memory set and probe stimuli.

An auditory version of the Sternberg task was employed by Pelosi et al. (1992a; 1992b) in two studies. The memory sets were composed of 1, 3, or 5 digits spoken in sequence. ERP averages were derived from the probe stimulus. In the first case, the sample was composed of 7 male and 19 female participants. In the second case, the sample was composed of 6 female and 13 male participants. Consistent with previous reports, an effect of set size was observed in both studies. An increase in the size of the memory set, from 1 to 3 to 5, resulted in longer latency and smaller P300 amplitude to the probe stimulus. In the first study (Pelosi et al., 1992a), there were no significant correlations between scores on the WAIS and P300 amplitude or latency. However, the P300 amplitude ratio of set 5 to set 1 was negatively correlated with full-scale IQ. In the second study, smaller P300 amplitude was associated with higher mental ability. Again, no P300 latency effects were reported. The authors describe and discuss the wide range of individual differences in the morphology of the waveforms that complicated the scoring of the obtained waveforms.

A visual version of the Sternberg digit recognition task was employed in a study reported by McGarry-Roberts, Stelmack, and Campbell (1992). Event-related potentials to both the memory set and the probe stimulus were recorded from 56 female undergraduate participants. The memory set consisted of 1 to 7 digits presented 20 times each in a random order. The probe stimulus was a single digit that was in the memory set on 50% of the trials. The ERP waveforms were derived by averaging across the range of memory sets for the YES and NO responses. Reaction time was defined as the button lift-off or response initiation time for the correct recognition of the probe stimulus. Reaction time was significantly faster for the higher groups. The salient ERP effects in this study were 1) larger P300 amplitude for the higher ability than lower ability group to the memory set stimuli, and 2) shorter P300 latency for the higher ability group to the probe stimulus.

The association between mental ability and P300 during the performance of a Sternberg task was extended considerably in a study reported by Houlihan, Stelmack, and Campbell (1998). As in the previous study by McGarry-Roberts et al. (1992), ERP waveforms to both the memory set and probe stimulus were recorded from a large sample (N=61) of female participants. In this study, however, the memory set was composed of consonant letters rather than numbers. The memory sets were 1, 3 or 5 letters in length presented 160 times each in random trials. The probe stimulus was a single letter that was in the memory set on 50% of the trials. The effect of set size on both reaction time and ERP waves was robust, with increased set size affecting 1) longer latency and larger P300 amplitude to the memory set stimuli, and 2) longer reaction time, longer latency and smaller amplitude to the probe stimuli. Higher ability participants exhibited longer latency, and smaller amplitude to the memory set than lower ability participants. With respect to the probe stimulus, the higher ability participants displayed larger P300 amplitude than did the lower ability participants.

Overall, these studies were of good quality. The effects of set size on the probe stimulus were consistently robust and in the expected direction (i.e., longer latency and smaller amplitude with increase in set size). The size of samples used in the studies ranged from adequate (Pelosi et al., 1992b) to impressive (Houlihan et al., 1998). The Sternberg paradigms that were used in the four studies were quite diverse, so that differences in the effects of individual differences in mental ability may be accepted. Nevertheless, the absence of a pattern of consistency with respect to the association mental ability and P300 latency and amplitude across these studies does not allow any firm conclusion.

In an early report, ERPs were obtained during the performance of a visual IT task that required the discrimination of the length of two lines (Zhang, Caryl, & Deary, 1989). The IT duration threshold, which was negatively correlated with a general mental ability measure (r = -.30; N=35), was somewhat lower than previous work, but attributable to the restricted range of ability of this mixed sample of undergraduate students. Although some ERP measures, notably P200 latency and P300 amplitude, were significantly correlated with the IT duration thresholds, they were not correlated with mental ability. The exception was a negative correlation between mental ability and a measure that described the time to maximum P200 amplitude from the point at which this wave crossed the baseline of the ERP (r = -0.34). The functional significance of this latency measure has not been explored. It is notable that exposure duration of the discriminative stimulus was fixed at the participant's estimated IT as soon as it was obtained, and that ERP waves were derived from repeated measures of that stimulus. In this procedure, the exposure duration of the discriminative stimulus is a confounding variable in the comparison of individual ERP waveforms. Also, eye movement and EEG artifacts were not removed from these ERP waveforms.

In a subsequent study (Caryl, 1994), the same stimulus presentation and recording apparatus was employed to pursue the work of Zhang et al. (1989). The sample was composed of 28 male and 28 female undergraduate students. Eye movements were not recorded but a stringent EEG rejection criterion was applied prior to ERP averaging. In the primary analyses, ERP waveforms were derived for a range of stimulus exposure durations, from 5 to 55 ms, and for each of three intervals defining the onset of the discriminative stimulus and the masking stimulus. Correlations with general mental ability were in the expected direction, negative for IT and P200 latency and positive for P300 amplitude, but the correlations were not significant at the .05 level of confidence. A measure that described the slope of the ascending portion of the P200 wave (i.e., the rate at which the peak amplitude of the wave developed), was significantly related to mental ability.

A visual inspection time paradigm that required the identification of lower case letters was also used to examine the relation of mental ability and P300 (Alcorn & Morris, 1996). The sample was composed of 49 participants, 22 males and 27 females. The stimulus onset asynchrony (SOA; defined here as the time from the onset of the discriminative stimulus to the onset of the masking stimulus) was varied from 17 to 100 ms in approximately 17 ms intervals.

ERP waveforms were derived for each SOA interval. Mental ability, as measured by Raven's Matrices, was positively correlated with P300 amplitude at temporal and occipital electrode sites for the 50 and 67 ms SOA (average correlation = 0.36). It was unusual that only data from an array of left hemisphere electrode sites were reported. No justification for this reduction was offered. P300 amplitude is maximal at midline central and parietal electrode sites in these types of discrimination tasks. It was puzzling that these data were not reported or recorded. At each SOA interval, the ERP waveforms were based on the repeated presentation of only 10 discriminative stimulus trials. This small number of trials does influence the signal to noise ratio of the averaging and the reliability of the waveform adversely.

In addition to the pattern reversal paradigm that was previously discussed, Burns et al. (2000) recorded ERPs during a visual inspection time task. In their procedure, a visual cue preceded the discriminative stimulus, which consisted of two vertical lines, and was immediately followed by a masking stimulus of 290 ms duration. Participants responded with a button press indicating the longer line. ERP waves were derived by averaging across a range of discriminative stimulus exposure durations. Shorter latency for early ERP waves, specifically P1, N1, and P2 were reported for higher ability participants at central midline and lateral occipital electrode sites. From the information provided in this report, it appears that these ERP waves were derived from the cue stimulus (i.e., a small circle) that preceded the discriminative stimulus by 425 ms, not the discriminative target stimulus. The P300 wave was not scored. From the figures of the ERP waveforms, it appears that the polarity of the recordings was, in fact, reversed. EEGs recorded to trials with an SOA of 20 ms or greater than the IT estimate of the participant were excluded from the averaging. This means that SOA is a confounding variable in the comparison of individual ERP waveforms. In this regard, it was reported that IT was positively correlated with the ERP waves. Again, however, there was some uncertainty of the stimulus, cue or target, on which the ERPs were based.

An auditory oddball paradigm with backward masking was employed by Bazana and Stelmack (2002) to examine individual differences in mental ability with ERP measures. The sample was composed of 36 women for whom data was collected using stimuli at 88 dB intensity. In a second study, the sample was composed of an additional 24 women. The same procedures and conditions were employed with additional intensity conditions of 76 and 82 dB tones. The stimulus discrimination task consisted of a series of infrequent target stimuli (700 Hz, 25 ms duration, 15% frequency of occurrence), intermixed with standard tones (600 Hz, 25 ms duration, 85% frequency of occurrence). On each trial, standard and target tones were followed by an auditory masking target stimulus (1000 Hz, 55 ms duration). The inter-tone interval (ITI) between the standard and tones was varied at 25, 50, and 150 ms in independent series of 70 trials. This procedure was presented first under a passive condition (i.e., where participants were asked to read a book and to ignore the tones) and an active condition (i.e., where participants listened to the tones and were required to identify each occurrence of the deviant stimuli.)

In the active condition, the performance of the higher ability group was significantly more accurate and response times were faster and less variable than the lower ability group across all three ITI intervals and intensity conditions. Effect sizes for these performance indicators were robust. Congruent to the performance measures, the higher ability group exhibited larger P300 amplitude and shorter P300 latency to the target tone across all ITI intervals. Effect sizes for the P300 amplitude measures were also robust. These effects were evidence of the greater efficiency and speed of information processing, independent of response production or execution, for the higher ability group.

The passive condition yielded an ERP measure, derived by subtracting the ERP wave to the standard stimuli from the ERP to the deviant stimuli, termed mismatch negativity (MMN) that is considered an index of automatic stimulus change detection. From the MMN analysis, larger amplitude and faster latency for higher than lower ability participants was observed, notably for the 25 ms ITI condition. Thus, there is some evidence that the greater sensory discrimination ability of the higher than lower ability groups is manifest in an automatic processing mode.

The Mismatch Negativity and Mental Ability

The MMN is a difference wave derived by subtracting the waveform generated by a standard tone from the waveform generated by the deviant tone. The MMN has a modal latency of between 50 and 200 ms, and is seen as an automatic deviance-detector mechanism. It is widely viewed as the triggering event for the orienting response (Snyder & Hilliard, 1976; Näätänen et. al, 1978).

MMN amplitude and latency have high short-term reliability although reliability is less pronounced at the individual level (Escera & Grau, 1996). The MMN is believed to originate bilaterally in generators localized in the primary auditory cortex (Hari et al., 1984) and in the right frontal lobe (Girard, Perrin, Pernier, & Bouchet, 1990). An important difference between the MMN and other endogenous components is that it can be elicited in the absence of awareness or attention. When a research participant is engaged in a distractor task, he or she is typically unaware of the stimulus pattern.

The functional significance of the MMN lies in its ability to index the contents of the auditory sensory buffer (Cowan, 1984). Latency to peak amplitude indicates the amount of time required to complete a sensory discrimination. Peak amplitude indexes the strength of the echoic memory trace (Winkler et al., 1995).

To date, only one study employed the MMN waveform in the examination of mental ability. Using an auditory oddball paradigm with backward masking, Bazana and Stelmack (2002) found that individuals with higher IQ had shorter MMN latencies than lower IQ participants. There were no group differences in MMN amplitude. Although this study clearly indicated performance differences, independent of attentional or motivational factors, there is a need to replicate these findings before we can safely conclude that individual differences in mental ability can be reliably estimated using attention-independent ERP measures.

Summary of Literature Review

The field of mental ability research has come a long way since pioneers such as Sir Francis Galton and Alfred Binet first began to investigate this concept. Advances in statistics such as the development of the correlation coefficient, factor analysis, analysis of variance, along with other technologies such as brain imaging have helped advance our knowledge of the subject. This advance has followed several independent pathways of progress.

After much acrimonious debate, there is now little doubt that individual differences in mental ability are primarily genetic in nature. Through a series of twin and adoption studies, behavioural geneticists have consistently shown that the role of environment, although modest during childhood, quickly disappears as a person matures. As a matter of fact, the IQ correlations between monozygotic is equal to the reliability of the IQ measure. The Human Genome Project is an ambitious endeavour that may identify the actual genes that contribute to individual differences in mental ability. Results so far have been modest but promising.

Although hampered by a continued lack of an operational definition of mental ability, Eysenck (1994) speculates that this need not be problematic. The field of psychometrics began in earnest in the late 1800s with Alfred Binet's development of a rudimentary IQ test. Since that time, IQ tests have been enhanced and continually improved to obtain a more reliable and valid measure. Although there are currently a slew of IQ tests on the market, the acceptable gold standard remains the Wechsler Adult Intelligence Scale – Revised (WAIS-R).

Various theories on the structure of mental ability exist, ranging from a single factor theory originally espoused by Spearman (1904) all the way to a multifactor theory such as Guilford's (1977) 120 separate abilities. This debate has been resolved by the impressive work of Carroll (1994) showing that a single unitary g factor exists, and is supported by eight-sub factors. As a result, the current consensus is that mental ability is hierarchical in nature, with a general factor and several stable sub-factors.

The use of information processing theories has provided a wealth of knowledge on the explanatory structure of mental ability. Studies have consistently shown that information processing, even in infants, is predictive of later IQ. A long series of studies have also shown that individuals with higher psychometric IQ have shorter response times to simple visual and auditory stimuli. These results generalize to more complex ECTs such as the Sternberg and Posner Paradigms. A more modest series of studies have also shown that mental ability is related to sensory discrimination. Perhaps the most impressive series of ECT studies have demonstrated that the time needed to make a very simple perceptual discrimination, (i.e., inspection time correlates strongly and consistently with IQ). Finally, a series of studies by Raz et al. (1983, 1985, 1987) has shown that frequency discrimination is also related to mental ability. Although impressive, ECT studies have failed to produce a theoretical framework to explain these results. Various explanations include cognitive speed and sensory discrimination ability.

A promising avenue is the use of biology in the study of mental ability. Individuals with higher IQ are known to have larger head and brain sizes, faster nerve conduction velocity, and lower rates of cerebral glucose metabolism. The largest body of research involves the use of event-related potentials. A series of studies have shown that individuals with higher IQ have shorter P300 latencies than lower IQ participants. Group differences in P300 amplitude are also apparent. A study by Bazana and Stelmack (2002) has also shown that mismatch negativity latency differences are also related to mental ability.

Although impressive, the field of mental ability research has also been hampered by a series of difficulties. They are discussed next.

Issues and concerns. When reviewing the literature, there were many limitations in the research that render the comparison between studies, and the generalizability of the results problematic. We will discuss three of these issues; the diversity of mental ability measures, sample size, and sampling.

Diversity of mental ability measures. There is no agreed-upon standard in the measurement of psychometric mental ability. Although the WAIS-R is the most widely used mental ability test, other researchers have used a wide range of assessment tools such as the Raven's Progressive Matrices and the Woodcock-Johnson Psycho-Educational Battery. These tests differ widely, not only in content, but also in structure. In the study discussed in this thesis, the Multidimensional Aptitude Battery (MAB), a group-administered analog of the WAIS-R is employed. On the surface, it would appear that this could potentially contribute to an additional source of variance that may make the comparison of one study to another very difficult.

There are two main reasons why this is not a major concern. First, most published IQ tests are highly intercorrelated. As previously mentioned, the WAIS-R is seen as the gold standard in mental ability measurement. When a new test is constructed, scores are invariably correlated with the WAIS-R. If correlations are low, the new test is deemed invalid and will not be used (Jackson, 1984).

Secondly, the general factor of mental ability is prominent in all widely-accepted mental ability tests. g is not a dichotomous variable that some tests reflect while others do not. Inspection of a great many factor analyses of the widest variety of mental ability tests reveals, without exception, that the test's g loadings are a perfectly continuous variable ranging from above 0 to below unitary. However, the g loadings are always positive, provided all of the tests are scored so that higher scores represent better performance. Every kind of mental test and every mentally demanding activity as required in school or in most occupations, is to some degree, loaded with g (Jensen, 1998). As a result, even though different psychometric tests are employed, they all measure the same construct. This is the reason why psychometric tests are highly inter-correlated, and why the specific test employed is of a lesser concern (Jensen, 1998).

Sample size. The field of mental ability research makes heavy use of the correlation coefficient to quantify the relation between two variables. As causality cannot be established, the work often centres on the development of correlates. Researchers speak not of biological or cognitive determinants of mental ability, but, rather, of biological or cognitive correlates. This over-reliance on a specific statistical measure is problematic, particularly in the context of biological studies.

Because of issues such as cost and time, these types of studies rarely employ large sample sizes. For the most part, studies are limited to a few dozen participants. The Pearson product-moment correlation typically requires 50 participants before the coefficient can be deemed stable. When using less than 50 participants, the correlation can be appreciably affected by outlier scores, thus spuriously overestimating or underestimating the relation between two variables. This is not as problematic in areas such as head size research because this small positive correlation has been repeatedly replicated. However, for studies using other measures (i.e., ERP or PET), many of these studies have not been consistently replicated. We must therefore view these results cautiously.

There are three solutions to the sample size issue. The first is to carefully screen the data for outliers. The removal of outliers will limit one participant's outlier scores to spuriously inflate correlations and overestimate an effect. The second is to simply use more participants in each study. This may not always be feasible considering that these studies are often very expensive. Therefore, the best solution may simply involve consistent replication of new findings. With consistent replication, large scale meta-analyses can be conducted and we can remain reasonably confident that the results are reliable.

Sampling. A common limitation to psychological studies is the over-reliance on participant samples composed primarily of university students. This is especially problematic in mental ability research where IQ ranges are much more restricted than in the general population. For example, in Bazana and Stelmack (2002), the IQ score was 114 with a standard deviation of 5.6. This is much different than the overall IQ average of 100 and a standard deviation of 15 found in the general populations. Participants groups are, therefore, much more homogenous. This has two implications.

First, it becomes very difficult to generalize the results from studies employing student participants. Conclusions must, therefore, be applied judiciously and cautiously because they may not apply to the general population. Secondly, correlations coefficients can be substantially attenuated with reduced variability. Although there are statistical corrections for this problem (Jensen, 1998), this correction is nevertheless a statistical manipulation that may, or may not, reflect reality.

Chapter Two

Introduction to the Present Study

The primary purpose of this research project is to explore the fundamental explanatory mechanisms underlying individual differences in mental ability. This will be achieved through the application of behavioural and psychophysiological methods to individuals performing an auditory oddball talk with backward masking. This work builds upon and extends a rich history of research indicating that individual differences in mental ability are related to differences in cognitive processing, sensory processing, or both.

In previous work, the relation between mental ability and auditory discrimination ability was examined by recording event-related potentials during an auditory oddball task with backward masking (Bazana & Stelmack, 2002). The higher ability group displayed greater response accuracy, shorter reaction time, larger P300 amplitude, and shorter P300 latency to target tones than the lower ability group across conditions that varied in intensity and in the interval between the target and the masking tones. The higher ability group also exhibited shorter mismatch negativity latency than the lower ability group when participants were instructed to ignore the stimuli. These effects contributed to the substantial literature that established a relation between higher mental ability and faster speed of information processing on elementary sensory, motor, memory, and decision tasks (Jensen, 1982; Vernon, 1990).

Although the differences between ability groups were robust, there were two somewhat surprising experimental effects that limited the understanding of those differences. First, the speed measures, reaction time, P300 latency and mismatch negativity latency were shorter at shorter inter-tone intervals. Second, variation in inter-tone interval had minimal effect on the accuracy of tonal frequency discrimination or on the event-related potential amplitude measures.

These results were surprising because shorter ITIs were expected to interfere with the processing of the target/deviant stimulus making the task more difficult. Shorter ITIs should lead to a reduction in accuracy, longer ERP latencies and reduced ERP amplitudes. The findings contradict expectations from an interference model of auditory masking that Winkler, Reinikainen, and Näätänen (1993) adopted in their work on auditory representation. The aim of the present study is not only to replicate, but also to extend the mental ability effects previously observed. Specifically, two additional experimental manipulations will allow a more direct examination of the underlying processes responsible for the observed effects. First, stimulus characteristics of the masking tone will be manipulated to examine the role of the masking stimulus. The results from this manipulation will allow a more direct determination of the underlying sensory and post-sensory mechanisms. Second, the base oddball task will be modified in some conditions by removing the masking tone. This will allow a direct investigation of the role of speed and sensory discrimination ability. Both of these manipulations will help forge the basis for a possible explanatory theory of mental ability; something that is lacking in previous work.

Backward Masking, Speed of Discrimination, and Mental Ability

Backward masking is a procedure that is widely employed to determine the amount of time required to extract information from a stimulus array (Sperling, 1960). The time between the offset of a task relevant stimulus and the onset of a masking stimulus is used as an index of the time required for a stimulus in sensory memory to be transferred to short-term memory. Initially, it was thought that the masking stimulus interrupted or interfered with the transfer from sensory memory to short-term memory. An alternative view suggests that the masking stimulus degrades the contrast of the target stimulus through a process of temporal integration (DiLollo, 1980; Eriksen, 1966).

Backward masking procedures were successfully applied to the study of individual differences in cognitive ability, notably the inspection time (IT) paradigm (Vickers & Smith, 1986). IT is defined as the minimum duration of exposure that is required for an observer to accurately discriminate between two stimuli that are easily discernible at longer exposure durations (e.g., the length of two vertical lines or the frequency of two tones). In a typical IT procedure, the target stimulus discrimination array is followed by a masking stimulus. Reviews of IT studies indicate a consistent and remarkably high relation (i.e., $r = -.50$) linking higher ability and shorter target stimulus exposure times (Bates & Eysenck, 1993; Kranzler & Jensen, 1989; Nettlebeck, 1987). Although most of the work on IT was in the visual modality, there are several studies employing backward masking procedures that demonstrated comparable effects with auditory discrimination tasks (Raz & Willerman, 1985; Raz, et al., 1983). In the Raz et al. work, the frequency and duration of the stimulus was held constant and the inter-tone interval was varied. A similar backward masking procedure is employed in the present study.

In several studies, ERPs were recorded during the performance of visual IT tasks. Zhang, Caryl, and Deary (1989) reported a negative correlation between mental ability and a measure that described the time to maximum P200 amplitude from the point at which this wave crossed the baseline of the ERP. In a subsequent attempt to replicate these findings, Caryl (1994) reported correlations with mental ability that were in the expected direction, (i.e., negative for IT and P200 latency and positive for P300 amplitude), but the correlations were not significant at the .05 level of probability. Alcorn and Morris (1996) also observed larger P300 amplitude for higher ability, whereas for Burns, Nettlebeck, and Cooper (2000), higher ability was associated with shorter latency for early ERP waves, specifically P1, N1 and P2. With the exception of Bazana and Stelmack (2002), no other ERP studies of mental ability applied backward masking procedures to the auditory modality.

P300, MMN, and Mental Ability

In a recent detailed review, it was noted that several investigators reported an association between higher ability and shorter P300 latency to the infrequently occurring target stimulus in an auditory oddball paradigm (Stelmack &Beauchamp, 2001). This effect was observed during passive conditions where participants were instructed to ignore the stimuli, and in active conditions where participants were instructed to count or respond to the target stimuli (O'Donnell, et. al, 1992). P300 latency values were negatively correlated with verbal learning and verbal fluency in passive conditions, with crystallized mental ability in the counting condition, and with concentration in the response condition (O'Donnell, et al., 1992). In a series of experiments employing an auditory oddball paradigm, Polich and colleagues observed consistent latency effects with correlations in the -.35 to -.45 range across several indices of mental ability (Ladish & Polich, 1989; Polich, Ehler, Otis, Mandell, & Bloom, 1986; Polich, Howard, & Starr, 1985; Polich & Martin, 1992). A negative relation between digit span and P300 latency in an auditory oddball paradigm was consistently observed across the life span by Walhovd and Fjell (2002). Perhaps because of the low difficulty level of these oddball tasks, few studies report significant correlations between P300 amplitude and cognitive ability (Vernon, et al., 1999).

The relation between mismatch negativity and mental ability was examined by Bazana and Stelmack (2002). Higher ability participants exhibited shorter MMN latency compared to lower ability participants. MMN amplitude was also significantly correlated with full-scale IQ at the shortest ITI period (i.e., 25 ms), with greater MMN amplitude for higher ability participants. These MMN results indicate that individual differences in mental ability involve an auditory discrimination process that proceeds automatically, without focused attention or conscious awareness.

The MMN was proposed as an index of the first stage in the development of auditory representation in the cortex (Näätänen &Winkler, 1999). The MMN effect is conceived as an expression of a pre-attentive mechanism marking the initial mapping of acoustic stimulation onto the physiological basis of sensory memory in the auditory cortex. In their 1999 review, Näätänen and Winkler placed considerable weight on a backward masking study of MMN by Winkler, et al. (1993) as evidence that MMN amplitude is a valid measure of sensory (echoic) memory. In their report, decreasing ITI had the effect of decreasing response accuracy during an active discrimination task and decreasing MMN amplitude during a passive, ignore condition. No MMN latency effects were observed (note that P300 latency and RT were not reported). An interference model was invoked in which the masking stimulus following the deviant tone is assumed to interfere with the processing of the tone to sensory memory.

Bazana and Stelmack (2002) used the same stimulus and procedure parameters as Winkler, et al. (1993). Although higher ability participants obtained higher accuracy scores than lower ability participants, decreasing inter-tone intervals had minimal effect on response accuracy or MMN amplitude. Similarly, although higher ability participants exhibited larger P300 amplitude than lower ability participants in all conditions, decreasing inter-tone intervals had minimal effect. That is, there was no task difficulty effect. Overall, an interference model could not be applied to these data. Moreover, while higher ability participants exhibited shorter

RT, P300, and MMN latency across all conditions, the decrease in these latency measures with decreasing ITI also contradicted an interference model. This temporal effect seems to implicate the masking stimulus, or the onset of the masking stimulus. That is, the target and mask may be perceived as a compound stimulus. The present study aimed to confirm this view and to replicate the mental ability effects that were previously observed.

In this current study, ITI and the tonal frequency of the masking stimulus are manipulated for participants who vary in mental ability. A control condition is also introduced in which the masking stimulus is white noise. If task difficulty, as indexed by response accuracy and P300 amplitude, is influenced by the masking tone manipulation, we could conclude that the masking stimulus is a primary feature of the sensory discrimination and that the target/deviant stimuli and the masking stimuli are integrated. Task difficulty is also manipulated here by varying the tonal frequency of the target stimulus in a no mask control condition. Examination of the interaction between mental ability, response accuracy, response speed measures, and the ERP latency and amplitude measures permits an assessment of the independent contribution of speed and discrimination ability to individual differences in mental ability.

Hypotheses

Based on previous results, we can expect to find the following:

1. The task performance of higher ability participants will be significantly better than the task performance of lower ability participants. This will be evident both behaviourally and psychophysiologically.
    a. These effects will be attributed to faster speed of auditory discrimination for the higher ability participants.

2. Task performance should be significantly reduced during shorter inter-tone interval conditions. Furthermore, we expect to find shorter reaction time, P300 latency and mismatch negativity latency during shorter ITI conditions.
3. We expect that mask type should have a significant effect on task performance. Task performance will be decreased when the tonal frequency of the mask is reduced. Furthermore, white noise will be a more effective masking stimulus.
    a. These mask type effects will be attributed to an integration framework rather than masking interference.

Chapter Three

Methods

Two separate studies were conducted as part of this investigation. For both studies, a psychometric measure of mental ability was administered. In the first study, an auditory oddball task with backward masking was presented. Inter-tone interval, defined as the time between the offset of the standard or deviant stimulus and the onset of the masking tone, was varied. The tonal frequency of the masking stimulus was also varied. The second study was designed to replicate the 1 KHz mask condition and to extend the examination of the effect of the masking stimulus on the discrimination and ERP measures. Conditions were introduced in which, 1) the pure tone masking stimulus was replaced by a white noise masking stimulus, and 2) the frequency of the deviant tone was manipulated without a masking stimulus.

Participants

The participants were English-speaking women recruited from introductory psychology classes. There were 30 participants in study I (M = 20.1 years; SD = 1.6 years) and 28 in study II (M = 21.4 years; SD = 1.2 years). All participants were asked to refrain from consuming caffeine or alcohol for 24 hours prior to the ERP data collection. All participants were non-smokers, right-handed, and were tested for normal hearing (15 dB ISO) at 500, 1000 and 1500 Hz using a Lafayette Instrument model 10D audiometer. Participants were also screened for drug use and history of brain injury. Participants were paid $40 after completing the study. Several factors were controlled during the careful selection and screening of research participants.

Ancillary measures

Age. By far, the most widely studied and understood demographic variable known to affect ERP waveforms is age. A large number of studies and reviews (e.g. Bashore, 1990;

Fuchigama, et al., 1995; Picton, 1992) have consistently shown that P3 latency increases linearly at a rate of approximately 0.9 to 1.7 ms per year in adult samples. The P3 amplitude results have been less consistent, but have generally shown a downward trend in amplitude in adult samples (Fabiani & Friedman, 1995; Picton, 1992). Mullis, Holcomb, Diner, and Dykman (1985) found that P3 amplitude on a visual oddball task increase up to the ages of 30-35 years, and then steadily decreases with ageing. P3 is also affected by developmental changes in people as they move from childhood to adulthood. In general, P3 latency becomes shorter as children age. Picton (1992) found that P3 latency decreases at a rate of 25 ms/year between the ages of 5 and 12, and then decreases at a rate of 1 to 5 ms/year up until age 18. Polich, Ladish, and Burns (1990) found that the amplitude of the P3 increases until age 13, after which it decreases slowly to adult levels. In the context of this study, participants ranged from 18 to 25 years of age with a mean age of 20.8 (SD=1.6) years. Therefore, development and aging would not contribute appreciably to the results.

Gender. Gender also affects P3 latency and amplitude in adult participants. P3 amplitude was affected by gender on an auditory oddball task employed by Cahill and Polich (1992). However, it appears that these amplitude differences were due to physiological factors such as head size and skull thickness, and not to any gender specific cognitive differences (Cahill & Polich, 1992; Ditraglia & Polich, 1991). P3 latency was also affected by gender on a mental rotation task (Desrochers, Smith, & Taylor, 1995). As a result, only female participants were employed in this study.

Handedness. Participant handedness also affects ERP waveforms. Brunswick and Rippon (1994) found that ERP lateralisation was affected by self-reported hand preference. In this study, all participants were right-handed.

Head size. The relation between head size and IQ is a well-documented and frequently replicated finding. A review of 54 studies indicates that the head size-IQ correlation was .20 after correcting for attenuation (Vernon et al., 1999). The assumption that external head size can serve as a proxy for brain volume is not unreasonable. The correlation between brain size and head size was approximately .60 for adults and .90 for children. In adults, the multiple R regression between multiple head size measures (i.e., height, width, length and circumference) and brain volume was .76 (Vernon et al., 1999). To control for possible mediating head size effects, three head size measures (i.e., length, width, and circumference) were obtained in this study.

Drug use. Certain drugs have also shown to affect ERP latency and amplitude. A number of studies have found that alcohol reduces the aplitude of the P3 wave and increases P3 latency (Campbell & Lowick, 1987; Campbell, Marois, & Arcand, 1984; Rohrbaugh, Stapleton, & Parasuraman, 1987). Caffeine also affects P3 amplitude and latency (Lorist, Snel, & Kok, 1994). Another common drug is nicotine. Edwards, Wesnes, Warburton, & Gale, (1985) investigated the role of smoking on P3 using a rapid visual information processing task in a sample of nicotine deprived male participants. P3 amplitude was not affected by nicotine, but P3 latency to correct detections was significantly affected. Norton, Howard, and Brown (1991) found that nicotine affected P3 amplitude in an auditory oddball task. Because of these potential effects, participants were asked to refrain from these substances for at least 24 hours prior to testing.

Certain other common drugs have also been found to affect ERP parameters, including scopolamine (Callaway, 1984), clonidine (Joseph & Sitaram, 1989), benzodiazepines (Milligan, Lumsden, Howard, Howe, & Dundee; 1989), and anti-histamines (Loring & Meador, 1989). As a result, participants were screened for current or previous use of psychoactive medications.

Language. Another obvious confound affecting psychometric mental ability evaluation is language. Participants not fluent in English would have difficulty completing the IQ measure. However, restricting the participant sample to participants who spoke English as a first language obviated this problem.

Other factors. Due to the relative lack of previous effect sizes, or because of ethical or design limitations, certain other factors were not accounted for in this study. One such factor was time of day. Although several studies failed to find a significant relation between time of day and ERP parameters (Geisler & Polich, 1990; Geisler & Polich, 1992), time of day was found to interact with food intake. Bazana (2001) did not find a consistent relation between time of day and task performance. Seasonal variations have also been shown to affect P3. Polich & Geisler (1991) found that P3 amplitude was largest during the spring and summer, and smaller during the fall and winter. However, P3 latency was unaffected. In this study, seasonal variations were not explicitly controlled, but the recordings coincided with the fall session.

The exclusive use of female participants raises the possibility that menstrual cycle could appreciably affect the ERP findings. In a visual oddball study using emotionally-laden stimuli conducted by Johnston & Wang (1991), P3 amplitude was found to increase significantly during ovulation. However, Fleck & Polich (1988) failed to find any effect of menstrual cycle when neutral stimuli were used. Using a very similar paradigm auditory oddball task with backward masking, Bazana (2001) failed to find any significant effect of menstrual cycle on behavioural or ERP measures.

Changes in arousal stemming from sleep deprivation have been shown to affect P3 parameters. Smulders (1993) tested normal young participants twice, once when they were sleep deprived and once when they were not. Not surprisingly, P3 amplitude was smaller, and P3 latency was longer in the sleep-deprived group. Due to methodological limitations, it was impossible to restrict the amount or quality of sleep prior to data recording.

Finally, certain clinical disorders are related to ERP parameters. For example, P3 amplitude decreased in adult participants with schizophrenia (Blackwood, Young, & McQueen, 1991), autism (Dawson, Finley, Phillips, Galpert, & Lewy, 1988), depression (Diner, Holcomb, Dykman, 1985), dementia (Goodin, Squires, & Starr, 1978), alcoholism (Pfefferbaum, Ford, White, & Mathalon., 1991), and multiple schlerosis (Newton, Barrett, Callaghan, & Towell, 1989). In children and adolescents, attention deficit-hyperactivity disorder was related to P3 amplitude and latency (Holcomb, Ackerman, & Dykman, 1986). Due to ethical and confidentiality concerns, it was impossible to obtain a detailed psychiatric history from our participants.

Procedure

The studies were conducted in two sessions. In the first session, participants completed the Multidimensional Aptitude Battery (MAB; Jackson, 1984), a group-administered mental ability measure modeled on the WAIS-R. The MAB yields three scores: verbal IQ, performance IQ and a full-scaled IQ (FIQ). In order to assess experimental effects and interactions, participants were assigned to higher and lower ability groups based on a median split of FIQ. For study one, the mean FIQ for the higher ability group was 125.3 (SD = 7.1) and for the lower ability group, it was 105.6 (SD = 5.7), t (28) = 8.2, p = .001. For study two, the mean FIQ for the higher ability group was 125.5 (SD = 4.5 and for the lower ability group, it was 104.7 (SD = 8.3), t (26) = 8.1, p = .001.

In the second session, all participants were seated about 40 cm in front of a computer monitor in an acoustically buffered room and performed an auditory oddball discrimination task.

In both masking studies, the auditory oddball task consisted of a series of frequently occurring standard tones (600 Hz, 25 ms duration, 85% probability of occurrence) and infrequently occurring target tones (700 Hz, 25 ms duration, 15% probability of occurrence). The stimuli were presented binaurally through headphones. In all masking conditions, the duration of the masking stimulus that followed the standard and deviant tones was 55 ms. The intensity of all tones was 82 dB SPL as determined by a Bruel Kjaer model 1613 sound level meter. Inter-trial interval was 600 ms.

Independent variables. The ITI was varied at 150 ms, 50 ms, and 25 ms. Each condition consisted of independent blocks of 500 trials, 425 standard tones and 75 deviant tones, presented in quasi-random order with the restriction that deviant tones could not be presented consecutively.

In study one, the frequency of the masking stimulus was varied at 1000 Hz, 900 Hz, and 800 Hz in three independent conditions. The three mask frequency conditions and the three ITI conditions constituted a full factorial design that yielded nine experimental conditions. The stimulus presentation procedure for study one is illustrated in Figure 1.

--------- Insert Figure 1 about here --------

In study two, the 1 KHz mask condition was repeated. This served as a replication that assessed the reliability of the effects. In the white noise masking condition, the duration of the white noise masking stimulus was 55 ms and it had a 5 ms rise-fall time. In a no mask condition, the deviant tones were 700 Hz, 666 Hz, and 633 Hz and all stimulus features and presentation parameters were the same as the masking conditions.

All conditions were first administered to each participant using passive attention instructions and then presenting an active response discrimination task. In the passive phase, participants were asked to read a book of their choice and to ignore the auditory stimuli. When questioned at the end of the passive procedure, all participants reported that they were not aware of the presentation of the deviant tones. Conditions during the passive phase were fully randomized.

In the subsequent active discrimination task, participants were asked to rest their right index finger on the spacebar of a standard computer keyboard and to press the spacebar when they detected a deviant stimulus within the series of standard stimuli. Participants were instructed to respond as quickly and accurately as possible. All participants were given a practice session to ensure that they understood the instructions and the task. For the active discrimination phase, the 150 ms ITI, 1 KHz condition was always presented first. Subsequent active discrimination tasks were presented in random order.

Electrophysiological Recording

In both studies, EEG was recorded from 7 electrode sites (Fz, Cz, Pz, Fc3, Fc4, M1, M2) following the international 10-20 system (Jasper, 1958). All electrodes were referenced to the tip of the nose and a ground electrode was affixed to the centre of the forehead. Horizontal electro-oculogram (EOG) was recorded from electrodes placed 1 cm from the outer canthi of each eye. Vertical EOG was recorded from electrodes placed 1 cm above and below the upper and lower canthus of the left eye. EOG and data from M1 and M2 were recorded using Grass Ag-AgCl cup electrodes. Data from all other sites were recorded using an Electro-Cap International ™ (Eaton, OH) electrode cap. Inter-electrode impedance was less than 5 kΩ.

Data Screening

An offline EOG correction subroutine was employed with artifact rejection set at ±100 μV. Data were digitally filtered using a bandwidth of 3 to 12 Hz (3 dB roll-off). The EEG data were later reconstructed into single trial epochs that began 60 ms prior to stimulus onset and continued for 940 ms.

Dependent variables. The performance measures that were analyzed were: 1) accuracy, defined as the percent correct detections of the deviant stimulus (PCR); 2) response time (RT), defined as the time from stimulus onset to the press on the computer space bar; 3) the standard deviation of response time (SDRT); and 4) the number of false positive responses to the standard stimulus.

During ERP averaging, trials were classified for averaging as standard or deviant stimuli. In the active discrimination condition, trials were also classified as 1) correct non-responses to standards; 2) false positives; 3) correct responses to deviants; and 4) misses. Only correct non-responses to standards and correct responses to deviants were averaged. A computer assisted scoring routine (InstEP Systems; Montreal, Canada) was used to determine the amplitude and latency of the P300 wave. P300 amplitude was measured at Pz as the maximum peak amplitude from the pre-stimulus baseline between 280-440 ms except for the 633 Hz deviant in the no mask condition. For that condition, P300 was measured between 280 and 650 ms.

In the passive condition, MMN waveforms were derived by subtracting the averaged waveforms to the standard tones at Fz from averaged waveforms to the deviant tones at Fz. MMN amplitude was defined as the maximum amplitude of that difference waveform from the pre-stimulus baseline between 100-240 ms. The latency of the MMN waveform was determined as the time from the onset of the stimulus to the point of the maximum amplitude of the difference wave. All waveforms were also scored manually in order to ensure accuracy.

Data Analysis

Although two samples of participants were employed for the studies, it was expedient (for economy in the text) to combine the data in a multivariate analysis. The analysis of variance (ANOVA) was a 2 X 3 X 3 design, i.e., mental ability (i.e., higher vs. lower ability) with repeated measures on mask frequency (1 KHz study 1, 1 KHz study 2, 900 Hz, 800 Hz, white noise) and ITI (150, 50, 25 ms). In this design, sample 1 was nested for 1 KHz, 900 Hz and 800 Hz and sample 2 was nested for 1 KHz and white noise with repeated measures across these conditions and for ITI. The replication of the 1 KHz condition allows the assessment of the stability of the effects observed within the present project as well as in our previous work. A separate 2 X 3 ANOVA was applied to the no mask condition, that is, mental ability (i.e., higher vs. lower ability) with repeated measures on deviant tone frequency (i.e., 700, 666, and 633 Hz). Geiser-Greenhouse epsilon adjustments were applied to the degrees of freedom for all factors with repeated measures. For all analyses, a p value of less than .05 was used to determine statistical significance. These ANOVAs were applied to each behavioural response and ERP measure in independent analyses. For all individual comparisons between means, Tukey's honestly-significant-difference tests were used in these post hoc analyses, ($p < .05$). Only significant interactions are described. . Pearson product-moment correlations are also reported.

Assumptions. This type of analysis contains several assumptions that must be addressed in order to determine the appropriateness of these statistical analyses.

Outliers

Response times below 100 ms or above 1000 ms were excluded from the analysis based on the recommendations found in Jensen (1998). Responses below 100 ms are faster than humans' "physiological limit" for the time required for the transduction of the stimulus by the sense organ, through the sensory nerves to the brain, then through the efferent nerves to the arm and hand muscles. Responses longer than 1000 ms usually result from errors, momentary distraction, or lapse of attention. Omitting outliers from the participant's total score improves the reliability of the measurement.

Missing data

In a minority of cases (less than 5%), there were missing data. In most cases, missing data were found for ERP variables where a participant did not exhibit a waveform within the acceptable timeframe. Due to the relatively small sample size, it was not feasible to perform the analyses with missing data because of the default case-wise deletion setting on most statistical programs. As a result, the group mean was inserted when missing data was encountered. Although this approach would slightly decreases group variability, this data retention method was the most appropriate.

Power

A challenge in ERP studies is related to the issue of power, or, more specifically, the probability of committing a Type II error. This occurs when, due to a small sample size, significant relations do not emerge. A power analysis was not conducted although the highly significant results obtained indicated that the issue of power was not overly problematic. It should be noted that although a sample size of 58 seems small compared to other types of studies (i.e., survey data), it is seen as sufficient for ERP studies.

Normality

It is an assumption of analyses of variance that the dependent variable(s) should be normally distributed within groups. When group sizes are relatively large, the deviations from normality do not have an appreciable impact because of the central limit theorem, according to which the sampling distribution of the mean approximates the normal distribution. As the sample size was not very large for this study, normality was facilitated by the careful screening of outlier values. Normality could have been assessed by reporting kurtosis and skewness values. However, this additional step was not performed as the the F-test employed in this study is remarkably robust to deviations from normality (StatSoft Inc, 1998)

Homogeneity of variance

Another assumption of analysis of variance is that the sample variances in the different groups of the design are equal. If the variances in the two groups differ from each other, then adding the two groups together is not appropriate and will not yield an estimate of the common within-group variance. A visual inspection of the standard deviations reported in Tables 1 and 2 of this document indicate that there generally were no large differences in group variance. Furthermore, the F-test used in this study is also robust to all but very large violations of this assumption (StatSoft inc, 1998).

Sphericity and compound symmetry

In repeated measures ANOVA containing repeated measures factors with more than two levels, additional special assumptions enter the picture. Specifically, the compound symmetry assumption and the assumption of sphericity. The compound symmetry assumption requires that the variances (pooled within-group) and covariances (across participants) of the different repeated measures are homogenous. The sphericity assumption states that the within-subject model consists of independent (orthogonal) components. When the compound symmetry or sphericity assumptions have been violated, the univariate ANOVA table may generate erroneous results. The Mauchley test of sphericity can be used to evaluate whether this assumption is met, but Monte Carlo studies have shown this test to be overly sensitive departures from multivariate normality. As these assumptions rarely hold, various approximations such as the Greenhouse-Geisser or Huynh-Feldt algorithms are employed. For this research project, all reported *p* values are corrected using the Greenhouse-Geisser algorithm.

Chapter Four

Results

Inter-Study Reliability

Overall, results from 1000 Hz pure tone masking conditions in both experiments were very similar. A correlation analysis of the means for each variable in each of the 15 conditions (3 ITI x 5 mask types) indicates that percent correct response (r=.91), number of false positives (r=.85), response time (r=.99), P300 latency (r=.90), and P300 amplitude (r=.99) were highly correlated, $p < .01$. Standard deviation of RT (r=.46) and mismatch negativity amplitude (r=.40) were moderately correlated, $p < .05$. The reliability of mismatch negativity latency was lower (r=.02, ns).

Auditory Discrimination During The Active Response Task

The effect of ITI on behavioural performance measures. There were significant interactions between ITI and the mask type on PCR, $F(8,176) = 3.11$ $p < .005$; RT, $F(8,168) = 3.19$, $p < .005$; and SDRT, $F(8,176) = 3.66$, $p < .001$. In each case, the interaction was determined by the white noise mask where performance was significantly higher than all of the other mask types. Specifically, for the white noise mask, PCR was greater, RT was shorter and SDRT was smaller than for the other mask types.

Significant differences between ITI intervals were also observed for PCR, $F(2,44) = 7.85$, $p < .001$; FP, $F\ (2,44) = 7.52$, $p < .001$; and RT, $F(8,168) = 3.19$, $p < .005$. PCR was greater at the 150 ms ITI (M = 86%) and 50 ms ITI (M = 85%) than at the 25 ms ITI (M = 81%). In our previous work, these values were identical but the effect was not statistically significant. FPs were greater at 25 ms ($M = 2.76$) than at 50 ms ($M = 2.13$) which was greater than at 150 ms ($M = 1.82$). RT was shorter at 25 ms ($M = 413.6$ ms) and 50 ms ($M = 415.2$ ms) than at 150 ms ($M = 445.6$ ms). The RT effect is a replication of the shorter RT at shorter ITI that was reported in our previous work (Bazana & Stelmack, 2000).

The effect of the masking stimulus on behavioural response measures. Mask type had significant effects on response accuracy, false positive responses, response time and variability of RT. Mean PCR with the white noise mask (94%) was greater than in all other conditions, $F(4,88) = 14.93, p < .01$. Similarly, there were fewer FP responses for the white noise mask than all other mask types, $F(4,88) = 4.69, p < .01$. PCR for the 1 KHz mask for study I ($M = 85\%$), study II ($M = 83\%$) and the 900 Hz mask ($M = 82\%$) was greater than with 800 Hz mask ($M = 77\%$).

Reaction time with the 1 KHz mask for study 2 was shorter ($M = 403.6$ ms) than the 1 KHz study 1 ($M = 440.5$ ms), 900 KHz ($M = 449.0$ ms) and 800 KHz ($M = 476.7$ ms) masking stimuli, $F(4,84) = 57.93, p < .001$. The RT for the 800 Hz mask was also shorter than for the 1 KHz study 1 and 900 Hz masking stimuli. RT was shorter for the white noise mask ($M = 354.3$ ms) than all other frequency conditions. The SDRT for the white noise mask was smaller than all other mask frequencies, $F(4,88) = 6.79, p < .001$

Overall, the salient effects of mask frequency on the response measures are greater accuracy and shorter response time for the white noise mask than the frequency masks and lower accuracy and longer response time for the lower frequency mask than higher frequency masking stimuli. The mask frequency effect indicates that when the mask frequency was closer to the frequency of the standard stimulus and deviant target stimulus the detection of the deviant stimulus was more difficult.

Behavioural response measures during the no mask condition. In general, there were clear effects of frequency of the deviant tone on task difficulty, but there were no interactions with mental ability. There was a significant increase in response accuracy, when the tonal frequency of the deviant tone increased from 633 Hz ($M = 42\%$) to 666 Hz ($M = 74\%$) to 700 Hz ($M = 90\%$), $F(2,52) = 75.3, p < .001$. There was a corresponding decrease in FPs, 8.4, 2.6, and 1.5, $F(2,48) = 33.0, p < .01$. Mean RT also decreased with increase in frequency of the deviant tone, 508 ms at 633 Hz, 439 ms at 666 Hz and 395 ms at 700 Hz, $F(2,48) = 96.7, p<.01$. There was a corresponding decrease in the variability of RT, $F(2,52) = 13.9, p < .01$. All of these effects are indicative of greater task difficulty when the difference in frequency between the standard and target stimulus is diminished.

Mental ability effects on behavioural response measures. Compared to the lower ability participants, the performance of the higher ability participants during the auditory discrimination task, averaged across all conditions, was characterized by greater response accuracy, fewer false positive responses, faster response times and smaller variability of response time. There were no interactions of mental ability at the .05 level of confidence with any behavioural response measure for ITI or mask type factors.

Response accuracy was consistently greater for higher ability participants (**M** = 87.8%) than for lower ability participants ($M = 80.2\%$) across all conditions, $F(1,22) = 6.27, p < .02$. Similarly, higher ability participants exhibited fewer false positive responses ($M = 1.4$) than lower ability participants ($M = 3.1$), $F(1,22) = 7.79, p < .01$. Mean RT was shorter for higher ability participants (412.3 ms) than lower ability participants (437.2 ms), $F(1,21) = 13.09, p < .001$, and SDRT was smaller for HA (81.5 ms) than LA (92.3 ms), $F(1,22) = 7.07, p < .02$.

Although the manipulation of the frequency of the deviant tone in the no mask condition produced clear task difficulty effects, individual differences in mental ability were only observed for response time, $F(1,26) = 6.33, p < .05$. Higher ability participants exhibited shorter RT to the deviant tones at 700 Hz ($M = 381$ ms), 666 Hz ($M = 426$ ms) and 633 Hz ($M = 487$ ms) than lower ability participants, ($M = 407$ms, 450ms, and 525ms, respectively). It can be noted that in the correlation analysis greater response accuracy was associated with higher ability for the 700 Hz condition, $r = .52, p < .01$. The correlation between FIQ and the auditory discrimination measures for ITI and mask type are shown in Table 1.

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ERP Measures During the Active ResponseTask

The effect of ITI on P300 latency and amplitude. There was an interaction of ITI with mask type that was attributable to longer P300 latency for the 800 Hz mask than the white noise mask at 25 ms, $F(8, 224) = 2.57, p < .01$. Across all ITI, P300 latency was shorter at the 25 ms ITI ($M = 350$ ms) and 50 ms ITI ($M = 346$ ms) than at the 150 ms ITI ($M = 364.3$ ms), $F(2,56) = 7.61, p < .01$. The effect is a replication of the shorter P300 latency at shorter ITI that was reported in our previous work (Bazana & Stelmack, 2000).

A significant effect of ITI on P300 amplitude was obtained, $F(2, 56) = 8.55, p < .01$. P300 amplitude was larger at the 25 ms ITI ($M = 10.6$ µV) than at the 50 ms ITI ($M = 8.57$ µV). At the 150 ms ITI, P300 amplitude had an intermediate value ($M = 9.48$ µV). The larger P300 amplitude at the 25 ms ITI contradicts the typical task difficulty effect in which P300 amplitude is smaller with greater difficulty. The absence of a systematic effect across levels of ITI also suggests that this ITI effect on P300 amplitude may be spurious. The grand average ERP waveform for HA and LA groups (study I) at the 150 ms, 50 ms, and 25 ms ITI, averaged across the 1 KHz, 900 Hz and 800 Hz mask types are shown in Figure 2. The grand average ERP waveform for higher and lower ability groups (study II) at the 150 ms, 50 ms, and 25 ms ITI, for the 1 KHz and white noise mask types are shown in Figure 3.

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The effect of mask stimulus type on P300 latency and amplitude. P300 latency was shorter for the white noise mask ($M = 337.8$ ms) than for all other mask types, $F(4,112) = 3.45$, $p < .01$. There were no significant differences in mean P300 latency between masking stimulus types at the 1 KHz (study I, $M = 361$ ms; study II, $M = 354$ ms), 900 Hz ($M = 358$) and 800 Hz ($M = 356$ ms) mask frequencies. P300 amplitude was larger for the white noise masking stimulus ($M = 12.3$ µV) than for masking stimuli at 1 KHz (study 1, $M = 8.7$ µV), 900 Hz ($M = 8.6$ µV) and 800 Hz ($M = 6.8$ µV). Amplitude for the 1 KH mask (study 2, 11.3 µV) was also larger than for the 800 Hz mask. Overall, mask type did influence both P300 latency and amplitude with the effects, (i.e., shorter latency and larger amplitude, largely attributable to the white noise mask). These effects are consistent with the behavioural response analysis in that the shorter latency and larger amplitude are characteristic of easier discrimination tasks. The grand average ERP waveform for higher and lower ability groups (study I) for 1 KHz, 900 Hz and 800 Hz mask types, averaged across the 150 ms, 50 ms, and 25 ms ITI, are shown in Figure 2. The grand average ERP waveform for higher and lower ability groups (study II), for 1 KHz and white noise mask types at 150 ms, 50 ms and 25 ms ITI, are shown in Figure 3.

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In the no mask condition, P300 amplitude was larger for the deviant tones at 700 Hz ($M = 11.3$ µV) and 666 Hz ($M = 10.8$µV) than for the 633 Hz deviant tone ($M = 4.1$ µV), $F(2,42) =$

18.5, $p < .001$. Although P300 latency was shorter for the deviant tones at 700 Hz ($M = 364.9$ ms) and 666 Hz ($M = 369.0$ µV) than for the 633 Hz deviant tone ($M = 380.3$ µV), this was not a statistically significant effect, $F(2,42) = 1.5$, p = n.s. The grand average ERP waveform for HA and LA groups (study II) for the 633 Hz, 666 Hz and 700 Hz deviant stimuli in the no mask condition are shown in Figure 3.

Mental ability effects on ERP measures during the active response mode. Across all conditions, the mean P300 latency was shorter for higher ability participants (337.3 ms) than for lower participants (368.9 ms), $F(1,28) = 37.2, p < .01$. This was a robust effect that was apparent for 10 of the 15 ITI and mask types examined. In the no mask condition, shorter P300 latency for the HA participants ($M = 410$ ms) than for the LA participants ($M = 434.3$ ms) was also observed at all three deviant tone frequencies, $F(1,21) = 8.6, p < .01$.

HA participants exhibited larger mean P300 amplitude across all ITI and mask types (12.5 µV) than the LA participants (6.7 µV), $F(1,28) = 51.0, p < .001$. Again, this was a robust effect that was apparent for all ITI and mask types examined. In the no mask condition, there was a pattern of larger mean P300 amplitudes for HA participants (14.2 µV, 14.7 µV, and 13.6 µV) compared to LA participants (8.6 µV, 8.2 µV, and 9.1 µV) for the 633 Hz, 666 Hz and 700 Hz deviant tones respectively but this was not a statistically significant effect, $F(1,21) = 2.8, p = .10$. It can be noted that in the correlation analysis, HA was associated with larger P300 amplitude for the 633 Hz ($r = .38, p < .05$) and the 666 Hz ($r = .49, p < .01$) deviant tones. The correlation between full-scale IQ and P300 latency and amplitude for ITI and mask type are shown in Table 2.

.... Insert Table 2 about here ....

ERP Measures During the Passive (Ignore) Condition

The effect of ITI on MMN. For mismatch negativity latency, a significant interaction was observed for ITI and mask type $F(8, 224) = 2.64$, $p < .01$, that was largely due to the difference between MMN latency at 50 ms ITI,1 KHz mask (198.6 ms; study 1) and 25 ms ITI, white noise mask (152.1 ms). There was also an interaction of ITI and mental ability that was determined by the shorter mismatch negativity latency at 25 ms than 50 and 150 ms ITI for the HA group, $F(2,56) = 4.50$, $p < .02$. Although the main effect of ITI was also significant, $F(2,56) = 10.1$, $p < .01$, this effect was determined only by the HA group. Overall, mean mismatch negativity latency was shorter at the 25 ms ITI (166.4 ms) than at the 50 ms (179.8 ms) and 150 ms (178.3 ms) ITI. Again this result is consistent with the shorter MMN latency with shorter ITI observed in our previous work (Bazana & Stelmack, 2000) and with effects of ITI noted for reaction time and P300 latency. There were no significant effects of ITI on MMN amplitude. The grand average MMN waveform for higher and lower ability groups (study I) at the 150 ms, 50 ms, and 25 ms ITI, averaged across the 1 KHz, 900 Hz and 800 Hz mask types are shown in Figure 2. The grand average MMN waveform for higher and lower groups (study II) at the 150 ms, 50 ms, and 25 ms ITI, for the 1 KHz and white noise mask types are shown in Figure 3.

The effect of mask stimulus type on MMN. For mismatch latency, the white noise mask was shorter ($M = 157.3$ ms) than the 1 KHz mask (study 1, $M = 187$ ms; study II, $M = 175.9$ ms), the 900 Hz mask ($M = 176.6$ ms) and the 800 Hz mask ($M = 177.0$ ms), $F(4,112) = 15.4$, $p < .001$ However, MMN latency for the 1 KHz mask (study I) was longer than for the other frequency masking stimuli. These data reflect a task difficulty effect, (i.e., shorter MMN latency for the white noise mask that had the highest accuracy of detection in the behavioural analysis). This effect is contradicted, however, in the analysis of frequency masks. MMN latency for the

800 Hz mask was shorter than for the 1 KHz mask (study I) but lower accuracy was observed for the 800 Hz mask in the behavioural analysis. On the other hand, this effect did not replicate as there was no difference between MMN latency for the 800 Hz and 1 KHz mask in study II. There were no significant effects of mask type on MMN amplitude, $F(4,112) = 1.87$, $p =$ n.s.

The grand average MMN waveform for higher and lower ability groups (study I) for 1 KHz, 900 Hz and 800 Hz mask types, averaged across the 150 ms, 50 ms, and 25 ms ITI, are shown in Figure 2. The grand average MMN waveform for higher and lower ability groups (study II), for 1 KHz and white noise mask types at 150 ms, 50 ms and 25 ms ITI are shown in Figure 3.

In the no mask condition, as the tonal frequency of the deviant tone increased from 633 Hz, to 666 Hz, to 700 Hz, the mean amplitude of the MMN waveforms increased, 0.1 μV, -1.0 μV, and -1.8 μV, respectively, $F(2,44) = 10.8, p <.01$. This effect is consistent with many previous reports, (e.g., Ford, Roth, and Kopell, 1976), and supports the view that MMN indexes accuracy of sensory discrimination (Näätänen &Winkler, 1999). MMN latency did not differentiate the deviant stimuli in the no mask condition, $F(2,46) = 1.69, p = .20$. The grand average MMN waveform for higher and lower ability groups (study II) for the 633 Hz, 666 Hz and 700 deviant stimuli in the no mask condition are shown in Figure 3.

The effect of mental ability on MMN. Across all conditions, the higher ability participants exhibited shorter MMN latency ($M = 161.6$ ms) than LA participants ($M = 188.1$ ms), $F(1,28) = 83.9, p < .001$. This effect was observed within all levels of ITI and mask type. Averaged across mask type, HA participants displayed significantly shorter mean MMN latencies (170.6 ms, 164.5 ms, and 149.6 ms) than the LA participants (185.3 ms, 195.9 ms, and 183.1) for the 150 ms, 50 ms, and 25 ms ITI, respectively, $F(1,41) = 23.8, p < .01$. As indicated most clearly in the correlation analysis, the most consistent effects were observed at the 25 ms ITI.

Averaged across ITI, higher ability participants exhibited shorter MMN latency for the white noise mask (M = 143.9 ms) than the lower ability participants (M = 170.6 ms). Similarly, MMN latency was shorter for higher ability participants with the 1 KHz mask (study 1, M = 178.1 ms; study 2, M = 158.8 ms), than the lower ability participants (study I, M = 196.8 ms; study 2, M = 192.9 ms). For the 900 Hz mask, higher ability participants also exhibited shorter MMN latency (M = 163.3 ms) than the lower ability participants (M = 189.9 ms). The effect was also apparent for the 800 Hz mask where higher ability participants exhibited shorter MMN latency (M = 163.9 ms) than lower ability participants (M = 190.3). There were no differences in MMN latency between higher and lower ability participants in the no mask condition, $F(1, 23) = 2.09, p =$ n.s.

There were no significant differences in MMN amplitude between HA and LA groups, F < 1. Although the correlation analysis indicated a positive relation ($r = .41, p < .01$) between mental ability and MMN amplitude (negative) for the 1000 Hz mask in study II at the 150 ms ITI, (i.e., smaller MMN for HA), this effect was not evident in study I, nor any other condition, and must be regarded as a spurious effect. The correlation between FIQ and MMN latency and amplitude for ITI and mask type are shown in Table 3.

.... *insert Table 3 about here* ....

Ancillary results

Head size. Head length correlated significantly with performance IQ (PIQ; r=.26, p=.05) and had a near-significant correlation with full-scale IQ (FIQ; r=.25, p=.06). Head width was significantly correlated with performance IQ (PIQ; *r*=.29, *p*=.03) and FIQ (*r*=.28, *p*=.03). Head circumference did not correlate significantly with IQ. It is interesting to note that none of the head size-IQ correlations were negative or below .15, therefore replicating previous well-established findings (Vernon et al., 1999).

Verbal and Performance IQ. In addition to full-scale IQ, a correlation analysis of VIQ and PIQ with the behavioural and ERP measures was also conducted (see Tables 5 and 6). Specifically, PIQ was more strongly associated with task performance in 80 % of the conditions. For the electrophysiological indices, PIQ was more strongly associated with task performance than VIQ in 38% of the conditions.

Table 1

Mean Percent Correct Response, False Positives, Response Time, and Standard Deviation of Response Time by Ability Groups

			PCR (%)		FP		RT (ms)		SDRT (ms)	
MF	ITI	DF	HA	LA	HA	LA	HA	LA	HA	LA
1000^a	150	700	95.2 (4.2)	76.1 (14.5)	0.7 (0.7)	3.6 (3.1)	461.0 (51.2)	489.6 (50.8)	84.4 (8.2)	100.9 (12.2)
	50	700	91.0 (10.4)	80.6 (16.4)	1.7 (1.8)	3.3 (2.9)	431.2 (38.6)	439.3 (50.4)	83.9 (20.9)	96.1 (20.4)
	25	700	82.6 (15.3)	69.8 (17.2)	1.9 (2.2)	5.6 (5.5)	414.3 (26.5)	444.8 (29.5)	91.0 (26.3)	104.9 (15.6)
1000^b	150	700	90.8 (9.3)	81.5 (16.4)	0.8 (1.0)	1.5 (1.6)	423.6 (37.7)	445.4 (37.9)	89.6 (20.1)	96.0 (29.3)
	50	700	87.6 (9.0)	78.9 (16.9)	2.2 (3.1)	3.0 (4.3)	374.9 (29.3)	411.1 (26.6)	68.9 (23.0)	85.7 (22.2)
	25	700	82.7 (12.4)	75.3 (13.4)	2.2 (2.2)	4.2 (4.3)	373.8 (33.2)	408.3 (39.9)	83.0 (21.1)	90.5 (24.1)
900^a	150	700	83.5 (14.4)	73.5 (16.9)	1.8 (2.5)	3.3 (3.1)	474.8 (44.8)	495.7 (38.9)	84.4 (11.9)	101.7 (24.9)
	50	700	90.2 (9.9)	77.6 (16.3)	1.3 (2.6)	2.9 (3.0)	415.0 (44.7)	449.7 (57.0)	75.5 (18.6)	103.0 (13.2)
	25	700	84.3 (17.9)	68.3 (18.5)	0.9 (1.1)	4.7 (2.9)	430.1 (45.2)	461.1 (43.0)	90.3 (20.4)	98.9 (21.6)
800^a	150	700	83.2 (14.2)	70.8 (19.1)	2.6 (4.1)	3.3 (2.9)	492.1 (33.4)	510.9 (46.9)	89.1 (17.5)	94.0 (14.9)
	50	700	75.3 (18.7)	64.8 (15.3)	1.7 (5.5)	2.3 (4.8)	476.4 (43.0)	495.6 (40.5)	92.1 (17.4)	105.8 (17.0)
	25	700	81.1 (16.0)	66.5 (17.6)	2.3 (4.3)	2.0 (3.6)	456.6 (28.9)	475.9 (43.4)	87.1 (19.9)	106.3 (21.1)
WN^b	150	WN	97.0 (508)	91.0 (11.0)	0.4 (0.9)	1.4 (1.9)	337.9 (33.1)	375.5 (38.6)	60.7 (20.8)	72.1 (25.6)
WN	50	WN	95.8 (10.0)	92.4 (8.2)	0.4 (0.8)	1.2 (1.7)	333.7 (35.1)	369.9 (31.6)	68.7 (28.6)	79.6 (23.0)
WN	25	WN	95.9 (6.6)	91.3 (11.1)	0.9 (0.6)	1.6 (1.5)	334.2 (34.2)	361.1 (33.9)	69.7 (24.3)	83.1 (20.7)
NM^b	n/a	633	44.4 (22.5)	40.0 (23.7)	7.8 (5.8)	8.9 (7.3)	487.2 (38.2)	525.1 (31.8)	106.1 (22.4)	114.5 (33.4)
NM	n/a	666	80.6 (18.5)	69.1 (24.4)	2.4 (3.4)	2.7 (3.7)	426.3 (39.4)	450.2 (38.1)	86.1 (26.4)	85.4 (21.1)
NM	n/a	700	94.5 (7.5)	85.2 (15.5)	1.2 (2.2)	1.9 (2.7)	381.3 (39.1)	406.5 (26.8)	76.3 (27.0)	89.0 (21.3)

Note. Standard deviations shown in parentheses. HA = higher ability; LA = lower ability; ITI = intertone interval; MF = mask frequency; DF = deviant tone frequency; WN = white noise; NM = no masking stimulus; PCR = percentage of correct responses; RT = response time; SDRT = standard deviation of response time; FP = false positives.

^{a}N=30. ^{b}N=28.

Table 2

Mean P300 Latency, P300 Amplitude, MMN Latency, and MMN amplitude by Ability Groups

			P300L (ms)		P300A (µV)		MML (ms)		MMA (µV)	
MF	ITI	DF	HA	LA	HA	LA	HA	LA	HA	LA
1000^a	150	700	368.0 (35.9)	378.0 (43.1)	11.8 (3.5)	5.4 (4.0)	176.1 (39.9)	184.1 (27.7)	-2.9 (1.8)	-2.4 (2.1)
	50	700	343.5 (24.1)	390.4 (27.0)	14.3 (5.9)	6.6 (5.6)	190.0 (33.1)	207.8 (17.5)	-3.3 (2.5)	-1.9 (2.6)
	25	700	340.7 (34.7)	369.7 (30.6)	11.7 (5.1)	4.1 (3.7)	169.6 (33.7)	199.2 (21.4)	-2.3 (2.1)	-3.7 (2.1)
1000^b	150	700	371.8 (24.0)	374.2 (34.4)	17.3 (4.9)	8.3 (12.4)	167.3 (23.9)	196.0 (18.9)	-2.1 (2.7)	-3.4 (1.7)
	50	700	344.4 (27.9)	372.1 (38.6)	19.3 (5.0)	10.0 (4.7)	163.3 (40.2)	192.4 (31.9)	-3.1 (2.7)	-2.8 (2.1)
	25	700	335.3 (22.1)	372.1 (37.1)	15.5 (5.7)	8.8 (6.2)	145.3 (36.6)	190.6 (25.3)	-3.5 (2.0)	-2.4 (1.9)
900^a	150	700	377.5 (44.9)	378.2 (35.3)	13.0 (5.7)	6.6 (5.1)	190.6 (36.8)	196.6 (18.4)	-2.2 (1.4)	-2.3 (2.3)
	50	700	342.6 (35.4)	384.6 (28.8)	12.9 (7.2)	5.7 (4.0)	153.7 (31.6)	188.4 (28.1)	-2.5 (2.0)	-3.5 (2.4)
	25	700	347.7 (31.5)	383.9 (33.5)	10.7 (4.1)	5.1 (2.9)	145.7 (27.5)	193.6 (33.9)	-2.2 (2.3)	-1.5 (2.6)
800^a	150	700	376.7 (43.2)	399.4 (28.5)	9.7 (4.1)	3.2 (4.1)	181.1 (36.8)	192.3 (31.7)	-2.6 (1.7)	-2.1 (2.3)
	50	700	339.8 (34.0)	384.6 (42.9)	10.0 (6.4)	4.7 (5.5)	142.6 (34.7)	176.3 (37.2)	-2.6 (1.5)	-1.9 (1.3)
	20	700	350.0 (38.4)	388.3 (34.7)	10.2 (4.8)	3.4 (5.9)	142.6 (34.7)	176.3 (37.2)	-1.9 (1.9)	-2.7 (1.5)
WN^b	150	WN	351.8 (20.8)	368.0 (37.3)	18.1 (7.9)	11.7 (6.4)	135.3 (31.8)	173.9 (26.7)	-2.7 (2.6)	-2.8 (1.6)
WN	50	WN	324.3 (39.8)	349.3 (36.6)	18.6 (6.8)	11.1 (6.4)	146.7 (18.9)	178.8 (28.1)	-2.2 (2.5)	-2.4 (2.0)
WN	25	WN	327.7 (32.9)	342.3 (41.7)	17.6 (5.8)	8.7 (7.6)	145.5 (25.5)	160.2 (38.3)	-2.8 (1.9)	-2.7 (1.8)
NM^b	n/a	633	527.9 (31.8)	543.9 (54.9)	14.2 (4.9)	8.6 (6.5)	168.1 (38.6)	177.6 (36.9)	0.5 (1.9)	-0.2 (1.9)
NM	n/a	666	355.5 (25.4)	377.7 (37.3)	14.7 (8.9)	8.2 (6.8)	160.9 (31.5)	169.4 (35.3)	-1.1 (2.1)	-1.0 (1.4)
NM	n/a	700	347.7 (23.4)	382.1 (42.3)	13.6 (7.4)	9.1 (6.7)	143.8 (35.4)	166.0 (33.1)	-1.9 (1.8)	-1.7 (1.3)

Note. Standard deviations shown in parentheses. HA = higher ability; LA = lower ability; ITI = intertone interval; MF = mask frequency; DF = deviant tone frequency; WN = white noise; NM = no masking stimulus; P300L = P300 latency; P300A = P300 amplitude; MML = mismatch negativity latency; MMA = mismatch negativity amplitude.

^{a}N=30. ^{b}N=28.

Table 3

Correlations between behavioural performance measures and verbal, performance, and full-scale IQ

			PCR (%)			RT			SDRT (ms)			FP		
MF	ITI	DF	VIQ	PIQ	FIQ	VIQ	PIQ	FIQ	VIQ	PIQ	FIQ	VIQ	PIQ	FIQ
1000[a]	150	700	.48**	.54**	.56**	-.52**	-.45*	-.53**	-.31	-.48**	-.44*	-.41*	-.55**	-.52**
	50	700	.52**	.61**	.59**	-.46*	-.55**	-.53**	-.49*	-.64**	-.60**	-.36	-.61**	-.51**
	25	700	.49*	.61**	.59**	-.56**	-.62**	-.64**	-.42*	-.54**	-.52**	-.55**	-.62**	-.56**
1000[b]	150	700	.44*	.53**	.52**	-.39*	-.35	-.40*	-.13	-.30	-.24	.01	-.45*	-.30
	50	700	.47*	.45*	.49**	-.32	-.60**	-.54**	-.23	-.49**	-.41*	.03	-.17	-.11
	25	700	.42*	.49**	.50**	-.55**	-.61**	-.61**	-.20	-.35	-.31	-.24	-.44	-.38*
900[a]	150	700	.31	.36*	.39*	-.46*	-.32	-.44*	-.30	-.41*	-.39*	-.35	-.53**	-.47**
	50	700	.45*	.63**	.56**	-.37*	-.52**	-.49**	-.57**	-.69**	-.69**	-.34	-.51**	-.44*
	25	700	.52**	.57**	.59**	-.53**	-.52**	-.57**	-.40*	-.37*	-.41*	-.72**	-.68**	-.75**
800[a]	150	700	.41	.45*	.53**	-.36	-.41*	-.42*	-.08	-.25	-.20	-.25	-.36*	-.33
	50	700	.56**	.54**	.59**	-.46*	-.47**	-.50*	-.38*	-.52**	-.48**	-.31	-.59**	-.49**
	25	700	.42*	.61**	.54**	-.35	-.47**	-.43*	-.43**	-.53**	-.51**	-.33	-.55**	-.47**
WN[b]	150	700	.47*	.53**	.52**	-.23	-.41*	-.37	-.23	-.21	-.23	-.11	-.28	-.25
WN	50	700	.32	.44*	.41*	-.28	-.41*	-.40*	-.17	-.33	-.28	-.04	-.34	-.25
WN	25	700	.46*	.55**	.52**	-.26	-.26	-.29	-.18	-.21	-.22	-.34	-.47**	-.45**
NM[b]	n/a	633	.09	.17	.14	-.13	-.46*	-.38*	-.11	-.10	-.04	.01	-.20	-.13
NM	n/a	666	.42*	.22	.31	-.40*	-.34	-.38*	-.14	-.12	-.13	.09	-.06	-.01
NM	n/a	700	.48*	.53**	.52**	-.21	-.46*	-.38*	-.17	-.28	-.25	.02	-.24	-.14

Note. VIQ = verbal IQ; PIQ = performance IQ; FIQ = full-scale IQ; ITI = intertone interval; MF = mask frequency; DF = deviant tone frequency; WN = white noise; NM = no masking stimulus; PCR = response accuracy; RT = response time; SDRT = standard deviation of response time; FP = false positives.

[a]N=30 [b]N=28

Table 4

Correlations between event-related potential (ERP) measures and verbal, performance, and full-scale IQ

			P3L			P3A			MML			MMA		
MF	ITI	DF	VIQ	PIQ	FIQ	VIQ	PIQ	FIQ	VIQ	PIQ	FIQ	VIQ	PIQ	FIQ
1000[a]	150	700	-.14	-.05	-.12	.51**	.55**	.57**	-.23	-.14	-.18	-.11	-.21	-.18
	50	700	-.45*	-54**	-.57**	.35	.32	.42*	-.29	-.29	-.30	-.04	-.01	-.05
	25	700	-.56**	-.48*	-.54**	.40	.47*	.51*	-.56**	-.44*	-.55**	.33	.07	.20
1000[b]	150	700	-.05	-.04	-.06	.59**	.54**	.60**	-.34	-.45*	-.44*	.50**	.33	.41*
	50	700	-.38	-.47*	-.47*	.67**	.59**	.67**	-.49*	-.43*	-.48*	.02	-.13	-.08
	25	700	-.35	-.44*	-.45*	.49*	.57**	.57**	-.59**	-.55**	-.61**	.04	-.27	-.16
900[a]	150	700	-.24	-.06	-.15	.34	.50*	.45*	-.15	-.07	-.12	.23	.24	.23
	50	700	-.38	-.55**	-.52**	.38	.33	.40*	-.21	-.26	-.26	-.08	.04	.01
	25	700	-.46*	-.43*	-.52**	.39	.51*	.53**	-.30	-.60**	-.48*	-.08	-.08	-.12
800[a]	150	700	-.61**	-.29	-.45*	.50**	.44*	.51*	-.35	-.16	-.28	-.15	-.07	-.15
	50	700	-.56**	-.62**	-.62**	.24	.44*	.39	-.22	-.49*	-.39	-.01	.05	-.03
	25	700	-.50**	-.34	-.46*	.23	.40*	.37	-.57**	-.37	-.51**	-.28	.28	.25
WN[b]	150	700	-.31	-.32	-.34	.45*	.36	.42*	-.26	-.41*	-.37	.30	.15	.21
WN	50	700	-.43*	-.23	-.35	.32	.31	.36	-.62**	-.47*	-.59**	-.06	.14	.05
WN	25	700	-.29	-.06	-.18	.50**	.52**	.55**	-.34	-.32	-.35	-.10	-.13	-.13
NM[b]	n/a	633	-.23	-.25	-.28	.38	.34	.38	-.10	-.09	-.12	.08	.11	.12
NM	n/a	666	-.51**	-.50**	-.53**	.46*	.45*	.49*	-.09	.01	-.04	.21	-.03	.06
NM	n/a	700	-.41	-.33	-.40	.23	.22	.23	-.22	-.01	-.12	.09	-.08	-.01

Note. VIQ = verbal IQ; PIQ = performance IQ; FIQ = full-scale IQ; ITI = intertone interval; MF = mask frequency; DF = deviant tone frequency; WN = white noise; NM = no masking stimulus; P3L = P3 latency; P3A = P3 amplitude; MML= mismatch negativity latency; MMA = mismatch negativity amplitude.

[a]N=30 [b]N=28

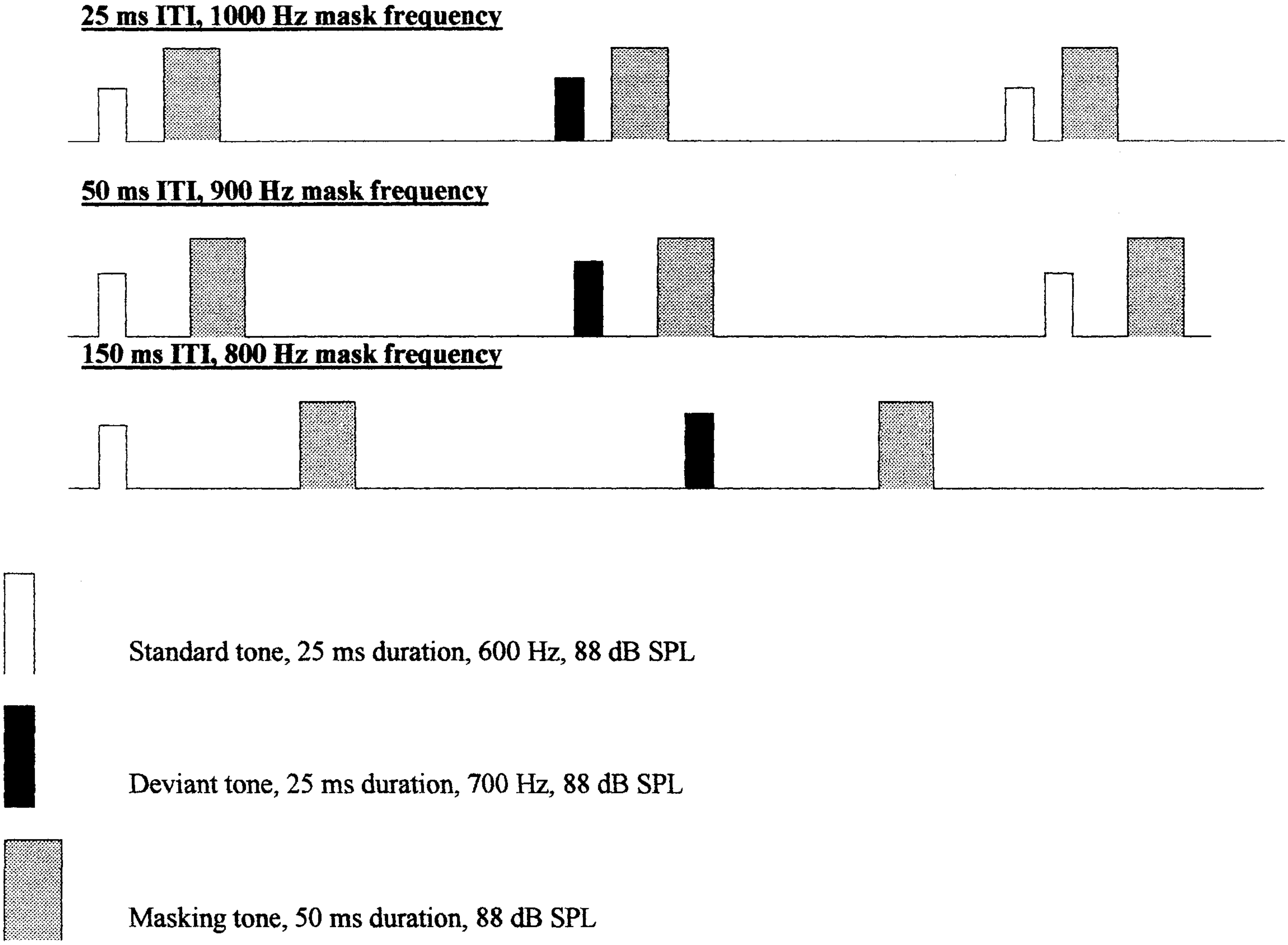
Figures Caption

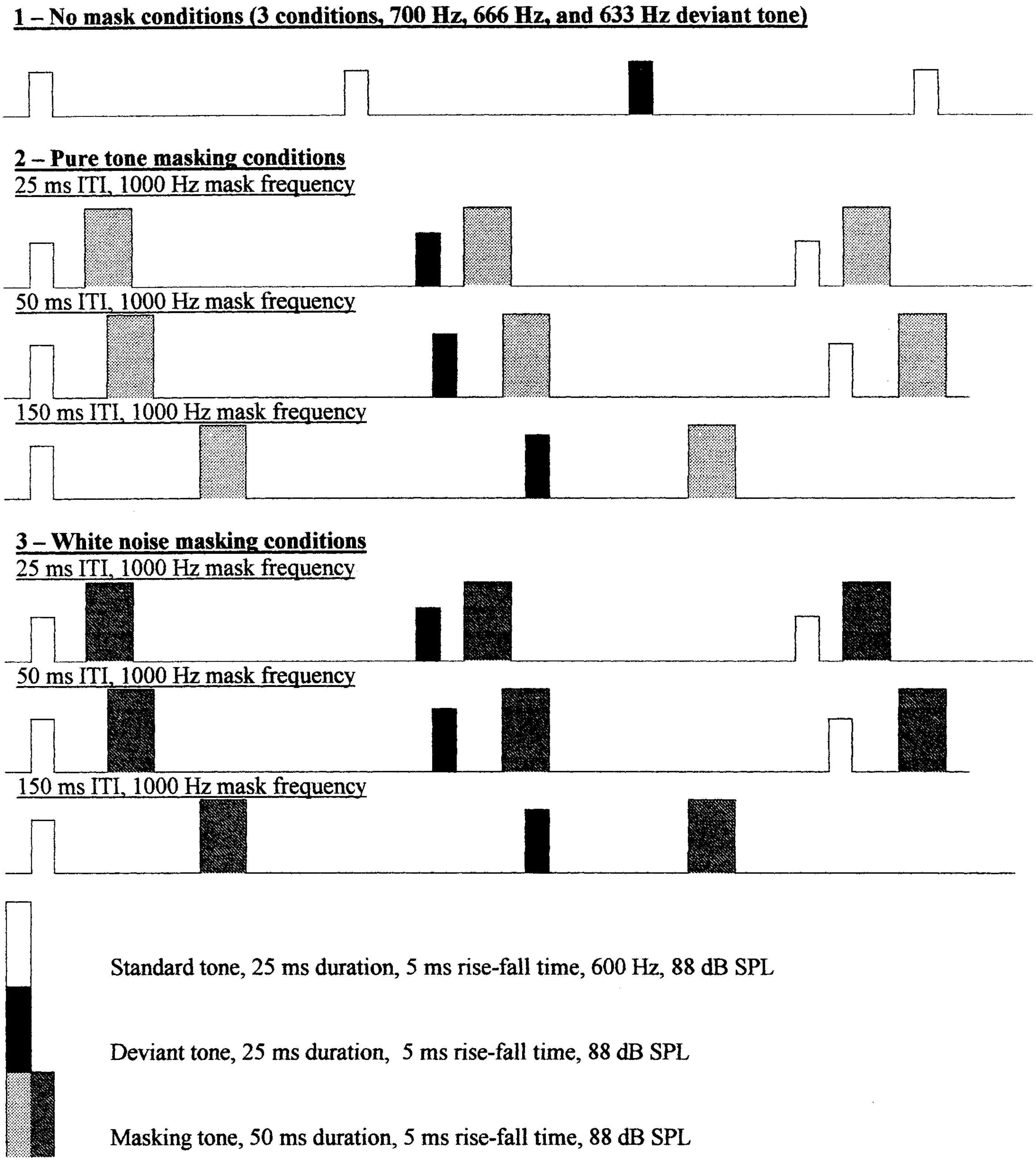
Figure 1. Illustration of stimulus parameters and timing sequence for the auditory oddball discrimination task with backward masking (Study I).

Figure 2. Illustration of stimulus parameters and timing sequence for the auditory oddball discrimination task with backward masking (Study II).

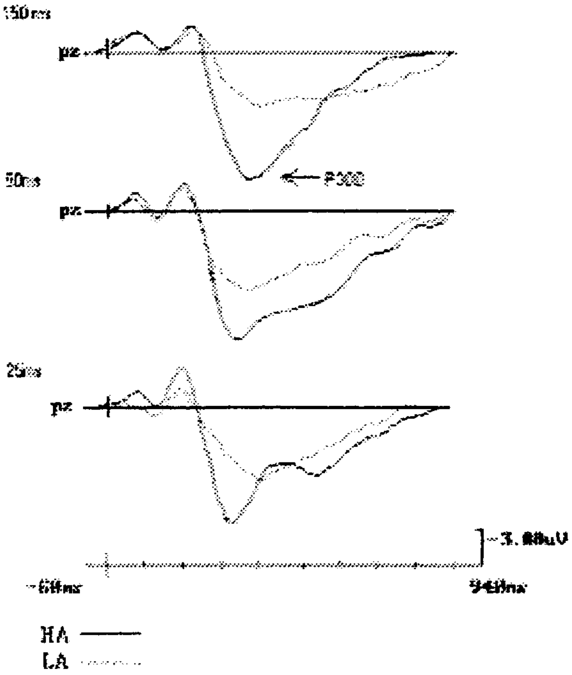
Figure 3. Grand average event-related potential waveforms recorded from the parietal (Pz) electrode site and mismatch negativity (MMN) waveforms from the frontal (Fz) electrode site for higher (HA and lower (LA) ability groups for 150 ms, 50 ms, and 25 ms inter-tone intervals (ITI) averaged across mask type and 1 KHz, 900 Hz, and 800 Hz mask types averaged across ITI (Study I, N = 30). The P300 and MMN waves are indicated by an arrow (↑). P300 and MMN latency is consistently shorter and P300 amplitude is larger for HA than LA.

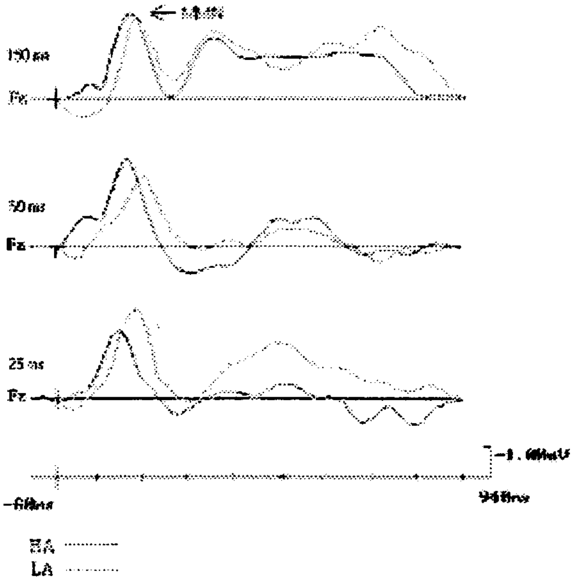
Figure 4. Grand average event-related potential waveforms recorded from the parietal (Pz) electrode site and mismatch negativity (MMN) waveforms from the frontal (Fz) electrode site for higher (HA) and lower (LA) ability groups at the 150 ms, 50 ms, and 25 ms inter-tone intervals (ITI) for 1 KHz tone and white noise mask types, and 633 Hz, 666 Hz, and 700 Hz deviant tones with no mask (Study II, N = 28). The P300 and MMN waves are indicated by an arrow (↑). P300 and MMN latency is shorter and P300 amplitude is larger for HA than LA.


25 ms ITI, 1000 Hz mask frequency
50 ms ITI, 900 Hz mask frequency
150 ms ITI, 800 Hz mask frequency
Standard tone, 25 ms duration, 600 Hz, 88 dB SPL
Deviant tone, 25 ms duration, 700 Hz, 88 dB SPL
Masking tone, 50 ms duration, 88 dB SPL

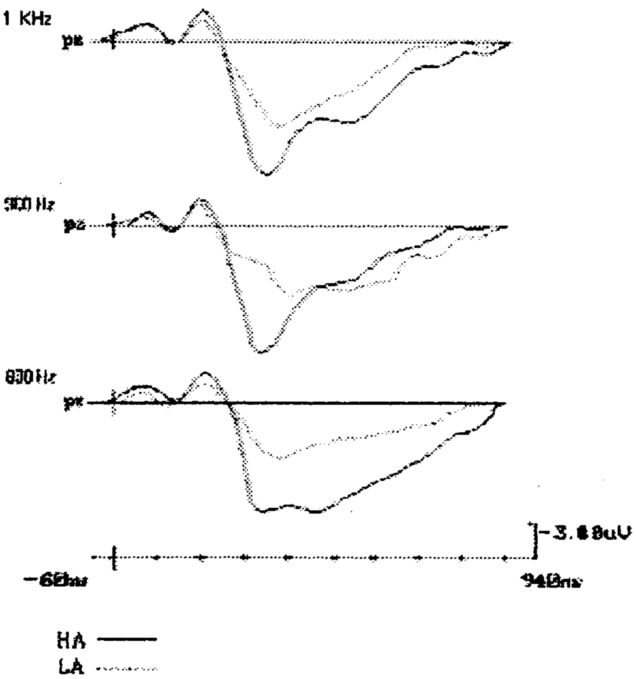

1 – No mask conditions (3 conditions, 700 Hz, 666 Hz, and 633 Hz deviant tone)
2 – Pure tone masking conditions
25 ms ITI, 1000 Hz mask frequency
50 ms ITI, 1000 Hz mask frequency
150 ms ITI, 1000 Hz mask frequency
3 – White noise masking conditions
25 ms ITI, 1000 Hz mask frequency
50 ms ITI, 1000 Hz mask frequency
150 ms ITI, 1000 Hz mask frequency
Standard tone, 25 ms duration, 5 ms rise-fall time, 600 Hz, 88 dB SPL
Deviant tone, 25 ms duration, 5 ms rise-fall time, 88 dB SPL
Masking tone, 50 ms duration, 5 ms rise-fall time, 88 dB SPL

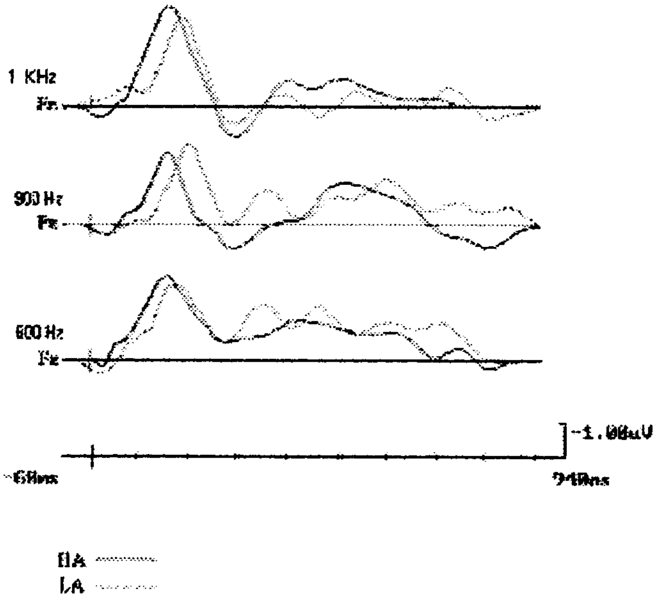
Inter-tone intervals

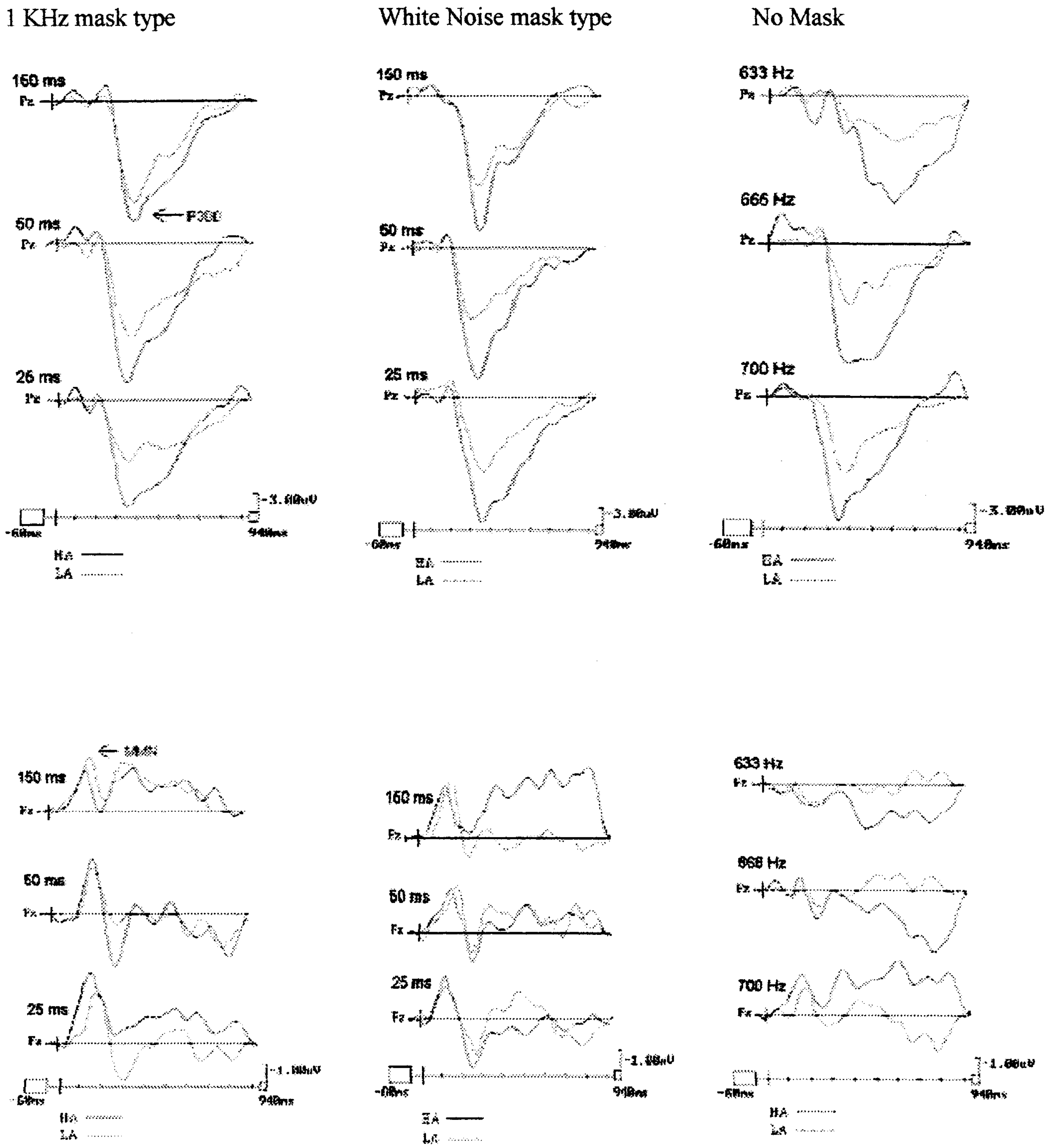




Mask type






1 KHz mask type
White Noise mask type
No Mask
150 ms
50 ms
25 ms
633 Hz
666 Hz
700 Hz
Pz
Fz
P300
MMN
-3.00uV
-1.00uV
-60ms
940ms
HA
LA

Chapter Five

Discussion

This chapter begins with a discussion of the primary analyses of this study. The convergence of behavioural and ERP measures in this study and with previous work is put forth. The constructs indexed by the behavioural and ERP measures are discussed in the context of the oddball paradigm employed in the research. It is argued that the pattern of results observed in the study support the view that speed of processing, rather discrimination ability, is the primary determinant of response accuracy. An attempt is made to outline a biological theory of mental ability through the integration of Eysenck's (1994) comparator model of mental ability and Näätänen's (1999) model of auditory stimulus representation. This is followed by discussion of ancillary data analyses, specifically analyses of verbal, performance and full-scale IQ, and brain size. Strengths, weaknesses and future directions are then discussed.

Discussion of Primary Analyses

The faster speed of auditory discrimination for higher ability than lower ability participants reported here is a pervasive and substantial effect that is evident at three levels of analysis, (i.e., behavioural response time, P300 latency during active responding, and MMN latency during a passive condition in which participants did not attend the stimuli). Higher ability participants also consistently exhibited greater response accuracy, fewer false positive responses, smaller response variability and larger P300 amplitude than lower ability participants. These results replicate the effects previously reported (Bazana & Stelmack, 2002) and there is a replication of the effects within the present studies for the 1 KHz mask condition. Overall, this evidence confirms that individuals with higher mental ability, as defined by psychometric mental ability tests, are characterized by better auditory discrimination ability and faster speed of processing.

This work underscores the value of the oddball paradigm for investigating individual differences in mental ability. It is also interesting to note that the classic auditory oddball paradigm, in which infrequent deviant stimuli are discriminated from frequent standard stimuli, without masking stimuli, was also successful in differentiating higher and lower ability participants. The mental ability effects for the no mask condition were not as robust as the stimulus mask conditions. No mental ability effects were observed for mismatch negativity latency in the no mask condition. Task difficulty could play a part in demonstrating the mental ability effects, although some significant differences were observed for both behavioural response and ERP measures for both easy and more difficult frequency discriminations.

The effects of inter-tone interval. Although response accuracy was lower and there were more false positive responses at the shorter inter-tone intervals, these effects were quite modest and there were no interactions with mental ability. Nor was inter-tone interval implicated in the P300 and mismatch negativity amplitude analysis that are known to reflect response accuracy effects. Both P300 and mismatch negativity amplitude vary directly with easier discriminations (Pritchard, 1981; Ford, et al., 1976). As in our previous work, inter-tone interval did not have the expected and desired effect on these measures that probe response accuracy.

The shorter reaction time, P300 latency and mismatch negativity latency with shorter inter-tone intervals that was observed in our previous report (Bazana & Stelmack, 2002) was replicated here. This result does contradict a task difficulty effect where longer latencies are expected for shorter inter-tone intervals. To our knowledge this effect has not been explored. Reaction time is not generally recorded in psychophysical masking studies and neither reaction time nor response latency has not been of interest in ERP research using masking stimuli. In general, the shorter response latency with shorter inter-tone intervals does seem to implicate the masking stimulus in the development of the response, suggesting that the masking stimulus is integrated with the standard and deviant tones and that they are perceived as a compound stimulus. A caveat here is that for higher ability participants, the mean latency at the 150 ms ITI (170 ms) is shorter than the time from onset of the deviant stimulus to onset of the mask (175 ms). It could be that the temporal interval, (i.e., offset of the target to onset of the mask), plays a more central role in the detection of the deviant-mask tone than is suggested by the integration of the deviant-mask as a single compound stimulus.

The effects of mask type. There were significant differences between mask types on both behavioural and ERP measures. Specifically, there was greater response accuracy and shorter reaction time for the white noise mask than other mask types. As the frequency of the masking stimulus was closer in frequency to that of the target and deviant stimuli, response accuracy decreased and reaction time increased. These effects clearly show that mask type influences the difficulty of the discrimination and confirm that the deviant and standard stimuli are integrated in the detection of the difference between them. For the ERP measures, the salient effect was shorter P300 and mismatch negativity latency and larger P300 amplitude for the white noise mask than the frequency mask types. Again, this reflects a task difficulty effect. Consistent with the behavioural effects observed here, shorter latency and larger amplitude are characteristic of easier tasks (Kok, 2001). It is interesting to note that the white noise masking stimulus was suggested by several colleagues as a possibly more effective than a frequency mask that would facilitate the effect of ITI on the response measures. Evidently, the broader frequency spectrum of the white noise stimulus allows a better resolution of the frequency deviant, (i.e., there is less integration of deviant mask), making the deviant stimulus easier to detect.

In summary, the view that the masking stimulus is integrated with the standard and deviant tones is endorsed by three observations: 1) reaction time, P300 latency and mismatch negativity latency are shorter at shorter inter-tone intervals, suggesting that the masking stimulus influences the response measures, 2) mask frequency type influences both behavioural and ERP measures, confirming that the standard-masking stimulus pair and the deviant-masking stimulus pair function as a compound stimulus, and 3) mental ability effects were observed in a frequency discrimination task without a masking stimulus for both behavioural (i.e., reaction time, percent correct response, false positives) and event-related potential (i.e., P300 latency and amplitude). This indicates that mental ability effects can be demonstrated with a single stimulus, although these effects were not as robust as those obtained when the masking stimulus was used. From the perspective of integration theory, the locus of analysis of stimulus features occurs at a sensory rather than post- sensory level (White, 1993; 1996).

Speed of auditory discrimination.

The shorter reaction and greater response accuracy for higher ability participants observed here accords with a burgeoning literature demonstrating that higher mental ability is associated with shorter reaction time on a wide variety of elementary cognitive tasks (e.g., Jenson, 1998; Vernon, 1990) and greater discrimination ability on simple sensory tasks (e.g., Deary, 2000). Inferences concerning speed and accuracy can also be made from the ERP measures. P300 amplitude decreases in conditions that impede information transmission such as degrading the stimulus array or decreasing stimulus exposure time (Johnson, 1986) and, as clearly shown in frequency discrimination task without the masking stimulus, for more difficult discriminations. It should be noted, however, that although P300 amplitude is indicative of sensory discrimination, it does not reflect the accuracy of discrimination because the ERP waveforms are based only on trials in which a correct response was made. From this perspective, the larger P300 amplitude of higher ability participants reflects their greater facility (i.e., speed) of information transmission in making the frequency discriminations.

P300 latency is widely regarded as a measure of stimulus evaluation time that is relatively independent of response selection and execution processes (Duncan-Johnson & Koppell, 1981; Kutas, McCarthy, & Donchin, 1977). This claim is based on evidence showing that when stimulus evaluation demands are increased, both response time and P300 latency tend to increase. However, when response processing demands are increased, reaction time often increases, whereas P300 latency does not increase appreciably. For example, on a Stroop task, where colour names were either congruent or incongruent with the colour in which they were printed, reaction time to the incongruent stimuli increased but P300 latency did not (Duncan-Johnson & Koppell, 1981; see also Doucet & Stelmack, 1999). On this view, the shorter P300 latency for higher ability compared to lower ability participants indicates that the greater speed of auditory discrimination of higher ability participants is not a due to differences in response strategy or test-taking experience as suggested by some authors (e.g., Mackenzie & Cummings, 1986).

The mismatch negativity wave is a sensitive index of change in auditory stimulation. It is conceived that the mismatch negativity is elicited by the comparison between representations in sensory memory of the frequently occurring standard stimuli and the incoming deviant stimuli. An important feature of the mismatch negativity is that it develops whether the stimulus is attended or not, and indeed, is relatively impervious to distracting conditions. In the present study, when questioned, participants indicated that they were not aware of any change in tonal frequency during the passive ignore condition. From this perspective, the shorter mismatch negativity latency for higher compared to lower ability participants is evidence of differences in the speed of an automatic discrimination process that develops without conscious awareness.

As observed in this study, mismatch negativity amplitude does decrease with more difficult discriminations. Thus, mismatch negativity amplitude was proposed as a means to probe stimulus discrimination ability (Näätänen, & Alho, 1997). It is notable that there were no differences in mismatch negativity amplitude between higher and lower ability groups. This leads to the question whether speed of discrimination or discrimination ability (i.e., perceptual sensitivity) is the root of the higher accuracy of discrimination for individuals with higher mental ability

There are several observations that support the view that the accuracy effects observed are determined by processing speed. First, the shorter reaction time, P300 and mismatch negativity latency are robust and pervasive effects. Second, these measures are shorter for shorter ITI is contrary to perceptual discrimination effects. The value of these measures would be expected to be longer with decrease in ITI were a discrimination ability factor. Third, because P300 amplitude decreases with increase in task difficulty, the larger P300 amplitude for higher compared to lower ability participants could be attributed to greater discrimination ability for higher ability participants, (i.e., the task was easier for the HA group). However, the P300 wave was derived only from trials on which a correct response was made. Therefore, from this perspective, the level of discrimination (100%) for P300 was the same for higher and lower ability participants. One can speculate that speed is implicated in the amplitude effects if one assumes that larger amplitude is a consequence of larger nerve bundles firing in unison because neural transmission is faster for larger nerve bundles. Moreover, there is compelling evidence associating mental ability with larger brain size (Wickett, et al., 2000), an effect also observed in this study. Fourth, there are no interactions between mental ability and task difficulty for measures where task difficulty was a factor (percentage of correct responses and P300 amplitude). Higher ability participants are expected to perform better than lower ability participants on more difficult tasks. Fifth, mismatch negativity amplitude can be used as an index of discrimination ability. Despite clear task difficulty effects for MMN amplitude, (i.e., MMN amplitude was sensitive to the difficulty of discrimination), there were no MMN amplitude differences between groups.

Ancillary discussion

Head size. A series of low positive correlations were observed between three head size measures and full-scale IQ in this study. These results replicate the longstanding and well-established observation that individuals with higher IQ tend to have larger head size (Vernon et al., 1999). Several studies have indicated that head size is related to brain size (Vernon et al., 1999) and it is therefore not unreasonable to conclude that in this study, higher IQ individuals had larger brains. However, the relation between head size and IQ is not clearcut. It is still unclear if this relation is mediated by larger structural brain components or by the brain as a whole. Furthermore, it is still not known if individuals with larger brains possess more neurons, more glial cells, higher neuronal packing density, or a combination thereof. Although the head size results in this study replicate well-established effects, it is still difficult to arrive at any firm conclusions.

Verbal and performance IQ analysis. The relation between the dependent variables and verbal and performance subscales was also examined. Overall, performance IQ was more strongly associated with task performance but this effect was not represented by an obvious pattern. Behavioural and electrophysiological indices of performance on the auditory oddball task with backward masking were correlated with verbal, performance, and full-scale IQ indices of mental ability (see Tables 5 and 6). Specifically, performance IQ was more strongly associated with task performance in 80 % of the conditions, thus replicating findings from a meta-analysis conducted by Grudnik and Kranzler (2001). For the electrophysiological indices, performance IQ was more strongly associated with task performance in 38% of the conditions. These results are consistent with findings by O'Donnell et al. (1992). However, these differences tended to be relatively small and were not represented by an obvious pattern. In the context of this study, it would appear that the use of full-scale IQ as the basis for major calculations was justified.

Towards a Biological Theory of Mental Ability

In 1961, Furneaux proposed a theory of mental ability that referred to biological processes in a very general way. Näätänen's (1990) model of auditory representation and selective attention is relatively specific concerning the neural processes and the quantitative measures that index them. The conceptual frameworks outlined by these authors are complementary, however, in particular because a comparator mechanism is the central construct for both authors. Discussion of their proposals may lead to a better understanding of the biological processes that support individual differences in mental ability.

Furneaux postulated three independent factors, all contingent on speed, that were required for the solution of a psychometric test item: 1) mental speed, the time required for completing a single elementary neural operation within the search for a solution; 2) error production (i.e., accuracy), which was dependent on the number of elementary neural operations and the range of times required for solution; and 3) persistence, the length of time that a search for a solution was maintained. The search for a solution to a problem involved the examination of single elements (i.e., neurons or nerve networks) and bringing them into association with elements defining the problem. He postulated a comparator mechanism to enable this examination that served to "bring together the neural representations of the perceptual material embodying the problem, the rules according to which the problem has to be solved, and the particular organization of elements whose validity as a solution has to be examined (Furneaux, 1961, p. 185). " Furneaux proceeded to advocate the analysis of psychometric test item difficulty in terms of the time taken to solve the item and most of the research on the theory followed that course, with some success, but not without difficulties, e.g., Freason, Eysenck, and Barrett (1990). In the context of Furneaux's theory, and subsequent modifications of the theory (Eysenck, 1994), the nature of the comparator remains unspecified.

The attempt by Näätänen (1999) to delineate the neural substrate of auditory representation and selective attention is clearly coincident with the perspectives of Furneaux and Eysenck (1990). Näätänen's (1990) model subsumes two partly overlapping systems served by comparator mechanisms: 1) an automatic, preconscious acoustic analysis system that provides information about the flow of acoustic stimulation, and 2) a selective attention system of acoustic analysis that identifies specific, designated stimuli. With respect to the former, it is proposed that a transient-detector system monitors ongoing auditory input (e.g., standard and deviant tones) activating generator processes of the N1 ERP (i.e., a negative wave that develops about 100 ms after stimulation). The standard and deviant tones can be conceived as acoustic elements that may be featured in human speech and that are isolated for averaging the EEG activity that is elicited. The processing of these elements occurs at an early stage in the auditory path. Mental ability appears not to be related to this early activity that is indexed by N1 latency or amplitude (Bazana & Stelmack, 2002).

The activation of the N1 generator process, which varies primarily by changes in acoustic energy, inputs to 1) executive mechanisms (e.g., long-term memory processes) that may cause a switch in attention to conscious sensory perception processes, and 2) an acoustic memory store of previous sensory analyses. A permanent feature-detector system also processes physical features of the acoustic stimuli to the memory store where it is stored as a neural trace and where a comparator process is enabled. Repetitious presentation of the stimuli results in a strengthening of the trace. Presentation of a different (e.g., deviant) stimulus signals activation of the mismatch negativity generator that may initiate an attention switch to executive mechanisms if the signal is strong enough. Evidence that MMN is due to a comparison of acoustic traces, (i.e., the relation between stimulation rather than direct stimulation), rests on observations that MMN amplitude increases with increases in the difference between stimulus intensity even when stimulus intensity is reduced (e.g., Näätänen, Paavilainen, Alho, Reinikainen & Sams, 1987). In this context, the shorter MMN latency for higher ability participants reflects the greater speed in executing this automatic, preconscious comparison between acoustic traces input from the permanent feature detector and traces of previous stimulation in sensory memory.

Although Näätänen's model does focus on the auditory representation of simple acoustic stimulation, the model itself may be sufficiently general, or could be developed, to encompass higher order mental operations that are demanded by mental ability tests such as Raven's matrices and that clearly require a comparator process. ERP measures may be exploited for this purpose. For example, the mismatch negativity wave is elicited by changes in phonetic and semantic stimuli (Näätänen & Winkler, 1999). These effects could be applied to the study of verbal ability. There is also some evidence that higher mental ability is related to shorter P300 latency during the performance of elementary cognitive tasks, (e.g., Sternberg digit matching, synonym/antonym matching; McGarry-Roberts, Stelmack, & Campbell, 1992; Houlihan, Stelmack, & Campbell, 1998). This line of inquiry may also benefit by using the oddball procedure. The significant progress in understanding the neural basis of psychological experience, exemplified here by the work of Näätänen, may lead to an understanding of the neural bases of mental ability and to a complete biological model of mental ability as envisioned by Furneaux and Eysenck.

Strengths

The use of event-related potentials. As discussed in the introduction, there are some limitations with behaviourally-based studies; the most notable being that it is difficult to determine whether the observed differences are due to central or peripheral mechanisms. Therefore, a primary strength of this thesis involves the application of event-related potential procedures to examine and extend several well-established behavioural findings. The advantages of ERPs compared to behavioural measures stem from three sources:

1. ERP components may directly reflect brain functions, whereas most behavioural measures show the final common outcomes of a complex set of processes, and therefore, can be used only as indirect indexes of the process(es) of interest

2. Some ERP components (MMN) index pre-attentive central processes that cannot be directly addressed by behavioural measures
3. ERP components can provide information about the brain areas involved in the process(es) of interest

Participant selection. There are a variety of factors that can confound ERP studies, including such things as age, gender, handedness, and drug use. Although it would not be feasible to control for every potential confound, the selection of participants for this thesis was conducted meticulously and systematically. Every effort was made to limit or eliminate the effects of confounding variables.

Statistical considerations. Most studies of individual differences rely exclusively on correlational analyses. Although this is a valid approach, the analysis of variance techniques employed in this study permitted a more fine-grained analysis of the factors contributing to individual differences in mental ability. Although ANOVA techniques cannot replace correlations, they are a useful complementary tool that were used successfully in this study.

Limitations and Future Directions

Participant-related issues. There are a few participant-related issues that must be considered when interpreting these results. First, participants were self-selected volunteers from introductory psychology classes. Although participants were not given any direct academic incentives, it is possible that some individuals were motivated by a general interest in this type of study. Anecdotally, participants were very interested in the IQ, personality, and ERP components of this study and reported a willingness to perform exceedingly well. As a result, it is likely that the motivation shown by the participants in this study is not typical of the general population.

However, as group differences were also observed in the attention-independent mismatch negativity conditions, this limitation does not appear problematic.

Another participant-related issue is the restriction of range in IQ scores. For the combined sample, mean IQ levels were a full standard deviation above the norm (full-scale IQ *M* = 114.7, *SD*= 12.1). However, as higher and lower ability groups differed, on average, by a full standard deviation, it is unlikely that this restriction of range severely attenuated the statistical findings. As a result, statistical corrections for restriction of range were not employed in this present study.

Experimental design issues. By far, the most significant limitation to this study is its correlational nature in so far as IQ was not manipulated. Although consistent group differences and experimental effects were apparent, it was impossible to delineate a clear causal relation. Due to the inherent nature of mental ability studies, causal studies are ethically and practically very difficult to design. However, there are two promising avenues that will next be discussed.

Psychopharmacology

Psychopharmacological methods are an experimental, rather than a correlational design, and allow a direct assessment of causality. A recent study by Strachan et al. (2001) examined the role of nerve conduction velocity as an explanatory factor for individual differences in response time. The authors examined 16 healthy adult participants in counterbalanced hypoglycemia (i.e., low blood glucose) and euglycemia (i.e., normal blood sugar) conditions. Glucose levels were manipulated through a hyperinsulinemic glucose clamp procedure. Controlled moderate hypoglycemia temporarily and reversibly deranges cognitive functioning in a widespread manner (Deary, 1998). In Strachan et al.'s (2001) study, hypoglycemia affected digit symbol from the Wechsler test battery, trail-making from the Halsteid Reitan battery, and speed of information processing from the British Ability Scales. Furthermore, decision time and movement time on an response time task, along with inspection time were significantly slowed during hypoglycemia. However, peripheral nerve conduction velocity in the arms and legs were unaffected. Although this is only one study that has not been replicated to date, results suggest that peripheral nerve conduction velocity is not causally related to individual differences in reaction time, inspection time, or mental ability.

Additional work has been done with the neurotransmitters related to mental ability. According to Stough (2001), a complete biological model of mental requires not only an understanding of brain structures and processes, but also an understanding at the neurochemical level. This understanding of the neurochemical processes would also facilitate an understanding of the genetic mechanisms of mental ability. Receptors and neurotransmitters are intimately involved in gene regulation (Stahl, 2000). A number of recent studies have implicated acetylcholine as an underlying factor.

Work in this area first developed from the observation that nicotine enhanced both mental ability test scores (Stough et al., 1994) and information processing correlates of mental ability (Bates et al., 1995). In an attempt to understand this effect, Stough et al. (2001) hypothesized that mental ability was predominantly mediated by cholinergic neurotransmission.

To date, there is substantial evidence that supports the link between mental ability and cholinergic transmission. Individuals with nicotine receptor loss (i.e., insulin induced hypoglycemia, Alzheimer's Disease) show impaired cognitive functioning compared to age-matched controls. Furthermore, nonsmokers performed significantly better on an information processing task following the application of a nicotine patch (Stough, Thompson, Bates, & Bates, 2001). These findings were replicated using nicotine administration through a gum (Pyman, Nathan, Thompson, & Stough, 2002). Also, the administration of the nicotine receptor antagonist mecamylamine acutely impairs performance on a cognitive task. Conversely, the administration of donepezil, an acetylcholinesterase inhibitor, improves performance. Finally, the blocking of muscarinic acetylcholine receptors using scopolamine impaired performance on a cognitive task.

Genetics

By far, the most promising future avenue of research is in the field of molecular genetics. Complex traits such as mental ability are likely due to multiple genes of varying but small effect size, rather than one gene or a few major genes. Genes in a multiple gene system are inherited in the same way as other genes but they have been given a different name – Quantitative Trait Loci (QTL) – in order to highlight some important distinctions. In the IQ-QTL Project, a systematic search for QTLs associated with normal variation in IQ was conducted. The IQ-QTL project has reported results from a preliminary genome scan of 1847 markers (Plomin et al, 2001). This project, thus far, has only uncovered QTLs which explain less than 1% of the observed variance in mental ability although more promising results are forthcoming (Plomin, 2003). The identification of genes responsible for individual differences in mental ability would also provide a clear and direct causal explanation of the observed differences, although much work needs to be done.

Conclusions

Overall, results indicate that the auditory oddball task with backward masking employed in this study successfully differentiated higher from lower ability participants on various behavioural and performance measures. Furthermore, these group differences appear to be due to a speed of sensory discrimination component that is related to individual differences in sensory processing. These results are also apparent in the attention-independent conditions indicating that individual differences in performance on mental ability tests are not due to confounds such as attention or motivation. These results replicate those by Bazana and Stelmack (2002) and have several implications. One cautionary note, however, is that the implications relate to mental ability, and not to scholastic ability or achievement.

Several lines of convergent evidence suggest that individual differences in mental ability are due to genetic and biological processes. Behavioural genetics studies show that environmental factors such as socio-economic standing, parental education, and educational funding only contribute to a small proportion of the observed variance. This study builds on those findings. As mental ability group differences were apparent in the passive-attention conditions, we can conclude that previous findings linking speed with mental ability are not due to attentional and motivational confounds.

Mental ability researchers speak of the "holy grail" of testing. In essence, they are searching for an elementary cognitive task that is so highly correlated with IQ measures that they can eventually replace the latter. The well-known limitations of IQ testing, including the reliance on language, attention, and motivation, would make the development of this task highly desirable. The auditory oddball task with backward masking was successfully related to IQ on a group level. However, the relation is not strong enough to advocate for the use of this paradigm in lieu of paper and pencil IQ testing. Nevertheless, significant progress was made toward this elusive goal.

The involvement of stimulus integration, rather than interference factors, also has several implications. The integration theory is sensory in nature whereas the interference theory provides a post-sensory (cognitive) explanation. Although the results from this study are not conclusive enough to advocate a change in education policies, the implication of sensory mechanisms may nevertheless prove to be an important contribution. Several education initiatives, such as the Head Start program or various special education programs, are based on an improvement in cognitive functioning. To a large extent, these programs have had limited success in increasing IQ scores over a long-term period. An enhanced understanding of mental ability, including a potential sensory component, could provide additional information needed to fully achieve these programs.

In recent years, the study of individual differences in mental ability has been relegated to a secondary role as more and more funding and research institutions focus on topics that are of immediate social relevance. The encouraging results from this research project should not be viewed as an end, but rather, as a valuable starting point for future research. There is perhaps no psychological trait that is more salient and pervasive than mental ability. Therefore, any future effort to further this research should be encouraged, not stifled.

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