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P300 and Cognitive Ability: *Processing Demands, Equivocation, and Speed of Processing During Simple Cognitive Tasks*

by

Michael Edward Houlihan

A document submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

School of Psychology
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Michael Edward Houlihan, Ottawa, Canada, 1994



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"...the more perceptive the senses are of
difference, the larger is the field upon which our
judgement and intelligence can act."

(Galton, 1911, p. 19)

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Curriculum Studiorum

Michael Edward Houlihan was born in Halifax, Nova Scotia on March 10, 1956. In 1976 he completed a Building Technology program from Dartmouth Regional Vocational School. He completed the first year of his undergraduate training at Dalhousie University in 1985/1986. He received an Honours BSc. with first class honours from Mount Saint Vincent University in Halifax, Nova Scotia in 1989 where he was awarded the governor general's medal for academic achievement. His undergraduate studies were supported by Mount Saint Vincent University Merit Scholarships and by the Natural Sciences and Engineering Research Council summer research program. His graduate studies started at the University of Ottawa in 1989. He was supported by the Natural Sciences and Engineering Research Council and the University of Ottawa Research Scholarship.

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Abstract

The hypothesis that individual differences in mental ability depend, in part, on the speed or efficiency of performing elementary cognitive tasks was examined. Performance and event-related potential measures were determined during the performance of a Sternberg memory scanning task with three levels of difficulty, a category matching task, and a synonym-antonym task. In each task two stimuli were presented sequentially on each trial. In the Sternberg task, the first stimulus was one, three, or five letters and is called the memory set. The second stimulus was a probe stimulus. A category name and a category exemplar were presented in each trial of the category matching task. The two stimulus words presented in each trial of the synonym-antonym task were either synonyms or antonyms.

Reaction time, movement time, and reaction time standard deviation were all negatively correlated with intelligence at levels consistent with previous research. In the Sternberg task, P300 amplitude to the first stimulus increased as the number of items in the memory set increased, affirming that P300 amplitude is sensitive to demands for processing resources. P300 amplitude to the first stimulus was smaller for higher ability than lower ability subjects. This is consistent with the idea that lower ability subjects require greater processing resources than higher ability subjects. The ERP differences between higher and lower ability subjects to the first stimulus were greater at fronto-central electrode sites than at Pz where P300 is maximal.

P300 amplitude to the target stimulus decreased as set size increased. This is consistent with the view that P300 amplitude is sensitive to changes in task difficulty. P300 amplitude to the second stimulus tended to be larger for the higher ability group, an effect

that can be understood in terms of equivocation.

P300 latency to both the first and second stimulus increased as the set size increased, affirming that P300 latency is a measure of the time required for stimulus evaluation and classification. Higher ability subjects displayed longer P300 latency to the first stimulus than lower ability subjects. The longer P300 latency to the first stimulus suggests that higher ability subjects devote more time to stimulus analysis and planning than lower ability subjects. The performance of higher ability subjects on these tasks was characterised by the more efficient deployment of processing resources and less equivocation than lower ability subjects. Speed of processing and speed of motor response were faster for higher ability than lower ability subjects.

Introduction

Psychometric studies of cognitive abilities have provided a general framework or descriptive structure of intelligence. While there is a consensus on the description of intelligence, relatively little research effort directed towards revealing the possible determinants of intelligence. In the present research, evoked potential (EP) measures of neural activity obtained during the performance of simple cognitive tasks are related to individual differences in psychometric intelligence. There is a good deal of evidence indicating that speed of processing, as indexed by reaction time measures in simple cognitive tasks, may be an important concept to explain individual differences in psychometric intelligence. In the present study, EPs are recorded concurrent with the performance of simple cognitive tasks. In particular, the latency of the P300 component, which reflects the time required for stimulus analysis and classification, will be used as an index of processing speed and related to intelligence.

The introductory chapter presents a discussion of the historical foundations of experimental research on intelligence and of the current views on the psychometric structure of intelligence. The application of EPs to individual differences in intelligence is relevant to questions concerning the contributions of constitutional factors to mental ability. Therefore, the main issues in this controversial subject are briefly reviewed. Specifically, arguments and evidence concerning the heritability of intelligence, the contributions of environmental factors, and the malleability of intelligence are outlined. Speed of processing is an important construct in EP studies investigating individual differences in intelligence. The traditional psychometric approach to the evaluation of intelligence has emphasized power rather than

speed. Speed refers to the time required to complete a task. Power refers to the ability to answer questions correctly without time constraints. The contrasts and similarities between measures of speed and power are reviewed. Because this study will employ simple cognitive tasks that have been used in reaction time studies, the recent work relating reaction time to speed of processing and intelligence is examined.

The view that mental abilities are associated with biological characteristics has a long history. The current status of attempts to relate intelligence to such biological measures as height and brain size are briefly noted. Evidence relating intelligence to biologically based measures using more recently developed techniques such as the speed of neural conduction, glucose utilization, and magnetic resonance imaging are briefly noted. EP correlates of intelligence have been examined over a 30 year period. The early work, focusing on sensory EPs, was undertaken in an effort to provide a culture-fair measure of intelligence. In general, the attempts to find a relation between intelligence and EP latency have not achieved this goal. More recent studies relating EPs to intelligence have focused on the use of the P300 component of the EP. The P300 component is particularly evident in response to novel, salient stimuli and is relatively insensitive to changes in the physical parameters of the eliciting stimulus. P300 latency has been employed as a measure of stimulus evaluation time that is relatively independent of response processes. These properties suggest that P300 latency could serve as an index of the speed of processing. In addition, P300 amplitude varies with demand for processing resources and also with task difficulty. It is possible that the efficient deployment of processing resources as reflected by individual differences in P300 amplitude could be related to psychometric intelligence. In light of these suggestions,

the P300 component will be described in terms of the experimental manipulations that lead to changes in its amplitude and latency. Following this discussion, studies that have related P300 measures to intelligence are reviewed. The chapter will close with a statement of the hypotheses that employ the EP methods briefly described above.

The Psychometric Description of Intelligence

The following section is devoted to a discussion of what is known about the constituents of intelligence. It is divided into two sections. The first part outlines the early historical foundations of the experimental analysis of intelligence. The second part describes more recent contributions to the understanding of the structure of intelligence.

Historical Background

The scientific investigation of intelligence can be traced to two separate sources in the 19th century. First, the establishment of a psychology laboratory in Germany by Wundt in 1879 paved the way for scientific investigation of psychological phenomena in general. The importance of this event lies in the resulting application of scientific methods to investigate psychological phenomena. Second, in England, Galton used Darwin's recently published treatise on evolution (Darwin, 1859) as an impetus for his initial studies into the nature of individual differences in intelligence (Galton, 1869). The tradition in Germany sought to reveal the essential elements of consciousness common to all individuals. In contrast, the tradition that developed out of the work of Galton stressed the explanation of the differences between individuals. Until recently, the distinctions between the two approaches were very pronounced.

Scientific advances in Germany at this time were leading to the establishment of

psychology as a distinct field of scientific inquiry. The work in Germany employed psychophysical methods as the tools of scientific inquiry. The methodology used in Germany involved few subjects and stressed repetition and long periods of testing. Galton, however, preferred to use many individuals and shorter tests. While the subject area and some methods of the testing were similar in Germany and England, the goals of the research and approach to investigation differed widely. For Wundt, an important objective was to discover general elements of conscious experience.

In Darwin's *On the Origin of Species by Means of Natural Selection* (1859) variability, continuity, and function were important concepts for describing progression in evolution. The concept of variability within species was important because evolution could not occur without it. Galton applied this concept of variability within a species to human intelligence. His works *Hereditary Genius* (1869) and *Inquiries into Human Faculty and its Development* (1911/1883) marked not only the beginning of the study of individual differences, but also the beginning of the extensive use of statistical methods in the science of psychology. Galton's interest in individual differences in mental ability was motivated in part by Darwin's theory of evolution. This theory stresses the individual's fitness. In this case, Galton applied individual differences in intelligence to fitness and evolutionary advantage. Intelligence, from this perspective, was described as "...an advantage-gaining factor in the evolutionary struggle" (Jastrow, 1901).

Galton opined that "*The only information that reaches us concerning outward events appears to pass through the avenue of our senses; and the more perceptive the senses are of difference, the larger is the field upon which our judgement and intelligence can act.*"

(Galton, 1911/1883, pp. 19). This dictum proposes that variability in mental ability can be referred to variability in simple sensory discrimination. Galton devised many measures of sensory discrimination to investigate intelligence. He invented a whistle that could vary pitch to test auditory perception. He devised a photometer to measure the ability to discriminate two spots of colour. He used a pendulum to measure reaction time to lights and sounds, and a series of weights to measure kinaesthetic sensitivity. Galton also evaluated olfactory discrimination and visual extension. Measurements also included anthropomorphic data such as height, weight, breathing power, strength of pull and squeeze, quickness of blow, hearing, vision, and colour sense.

The approach to data summary and description employed by Galton was revolutionary. He is responsible for the introduction of the concept behind the correlation statistic (Galton, 1888). This technique was mathematically formalized by Pearson, an associate of Galton.

Galton made many contributions to the study of intelligence. He provided the rationale for the individual differences approach to the study of intelligence within the context of evolutionary theory. Moreover, he provided empirical support for the heritability of intelligence (Galton, 1869). In this regard, he pioneered the basic methods for investigating heritability, the twin and adoption study methods. He also outlined an approach to study intelligence using reaction time and simple sensory discrimination.

In 1890, J.M. Cattell (who had studied with both Galton and Wundt) outlined a series of tests, in the Galtonian tradition, that he proposed for the measurement of mental abilities. Wissler, a student of Cattell, found that academic performance was not correlated with any

of these measures (Wissler, 1901). For many years this was taken as conclusive evidence that the approach advocated by Galton was essentially incorrect. The sample that was employed in Wissler's study was from Columbia University. The restriction of range of ability in this sample serves to lower observed correlations. More importantly, the methods of estimating reaction time and other tests of sensory and motor abilities were suspect to low reliabilities.

The Psychometric Structure of Intelligence

In his 1904 paper, Spearman noted that all measures of cognitive ability were positively correlated. From this observation, he developed the basic tenets of his theory of a general intellectual ability that is commonly called "g". Once the effects of unreliability were taken from a measure, Spearman believed that the measure could be split into two parts, one that reflected g and another portion specific to the test. The methods outlined in the 1904 paper also served as a basis for factor analysis. The methods of Galton and Spearman (correlation and factor analysis) became the methods of choice for investigation of the structure of intelligence. Acceptance of Spearman's g was not universal. Spearman later recognized that there were factors other than g that define intelligence. Overall, his work emphasized the importance of the general factor of intelligence.

Thurstone (1932) challenged the view describing intelligence in terms of a unitary or general factor. He advocated a model of intelligence that was comprised of several distinct mental abilities. He referred to these distinct factors as Primary Mental Abilities (PMAs). PMAs included processes of verbal comprehension, word fluency, number, spatial visualization, associative memory, and reasoning. In addition to the rejection of Spearman's view, Thurstone also rejected his methods for extracting or identifying factors. Thurstone

introduced easier computational methods of factor extraction. He also introduced factor rotation and the concept of simple structure. (Simple structure is achieved by rotating factors so that, as far as possible, each test has a large loading on only one factor and near zero loadings on all other factors.) The goal of Thurstone's mathematical procedures of factor analysis was to obtain simple structure. This contrasted with Spearman's approach to factor analytic methods that stressed the extraction of all that is common in the data. In changing this orientation, Thurstone developed rotation methods that allowed for correlated factors. The existence of correlated factors permitted further higher-order factor analysis and a hierarchical structure of intelligence. Higher-order factors raise the possibility that at the highest level a factor resembling Spearman's *g* would appear. In his earlier work, Thurstone preferred a theoretical approach that restricted his analysis to uncorrelated factors.

There was a substantial debate between those who viewed intelligence as a single factor versus those who preferred to describe intelligence in terms of several factors. Burt (1940) provided mathematical proof that the solutions derived by Spearman were mathematically equivalent to the results obtained by Thurstone.

The possibility of higher-order factor analysis resulted in formulations of a hierarchical structure of intelligence. Both Burt (1940) and Vernon, P.E. (1950) described hierarchical models of intelligence. Vernon explicitly portrayed a structure with *g* dominating two major factors of verbal-educational and spatial-mechanical. His verbal-educational factor subsumes more specific or narrower factors such as verbal, reasoning, numerical facility, and fluency. These narrow factors have a resemblance to some of Thurstone's PMAs. The spatial-mechanical factor dominates lower order factors of spatial ability, mechanical

information, and psychomotor coordination among others.

R. B. Cattell (1943) introduced the classification of fluid intelligence (Gf) and crystallized intelligence (Gc) which is often called Gf-Gc theory. Gf is derived from abilities of reasoning and higher mental processes. Gc subsumes those abilities gained through experience. Cattell and Horn (a student of Cattell) found evidence of these abilities in several factor analytic studies (Horn & Cattell, 1982; Horn & Stankov, 1982). Gf and Gc are normally found as second-order factors. In addition, second-order factors of Visualization Capacity, General Perceptual Speed, General Memory Capacity, and General Retrieval Capacity were found. These second-order factors are thought to be independent. This independence rules out the possible existence of a third-order factor that may resemble *g*.

The Gf-Gc model has been further expanded into an information processing hierarchy with different second-order factors at different levels of information processing (Horn, 1987). This formulation depicts levels of information processing of sensory reception, association processing, perceptual organization and education of relations. From this perspective, Gf and Gc are considered to be at the level of education of relations. Visual comprehension, speediness, and auditory comprehension are second-order factors at the level of perceptual organization. At the level of association processing are two memory factors, short-term acquisition and retrieval, and long-term storage and retrieval. In addition, Horn postulated a factor of correct decision speed at this level. At the lowest level of the information processing hierarchy are factors representing simple sensory awareness and discrimination. Factors at lower levels are suggested to provide input to factors at higher levels of the information processing continuum. The distinctions made in levels of processing are similar

to the distinction between Level I and Level II abilities suggested by Jensen (1968; 1970). Level I abilities involve sensory reception, storage, and recall of sensory inputs. Jensen's Level II abilities include reasoning, manipulation of information and abstraction.

A modified version of the Cattell-Horn Gf-Gc model was proposed by Gustafsson (1984; 1988). His HILI (hierarchical Lisrel based) model postulated primary factors similar to Thurstone's PMAs. Second-order factors included Gf, Gc, and general visualization (Gv). In addition, Gustafsson suggests a single third-order factor that is similar to Spearman's *g*. Furthermore, Gustafsson (1984) argues that Gf is conceptually identical to *g*. It appears, however, that the tests used in these studies may have been selected on the basis of their representativeness of the factors they were thought to measure. A more appropriate selection criteria would be to sample a wider range of abilities. However, this is often quite difficult.

The most comprehensive treatment of the structure of intelligence has been presented by Carroll (1993). This work was based on the reanalysis of over 400 data sets that were used to explore the structure of intellectual abilities. From this reanalysis, Carroll identifies three strata of factors. A general factor of intelligence can be found at stratum III, the highest order of analysis. At stratum II there are several broad abilities Gf, Gc, general memory ability, broad visual perception (Gv), broad auditory perception, broad retrieval ability, broad cognitive speed and processing speed. Carroll assumed that the factors were intercorrelated at all three strata. Stratum I includes many narrower abilities representing greater specialization of the broader abilities. Carroll suggests that the lowest stratum factors could be affected by experience and the adoption of strategies.

Carroll depicts the relation among second stratum variables Gf and Gc as more highly

correlated with *g* than other second stratum factors. The second stratum factors of general memory ability, broad visual perception, broad auditory perception, broad retrieval ability, broad cognitive speed, and processing speed exhibit decreasing degrees of correlation with *g*. Furthermore, Carroll indicates that the more popular clinical measures of intellectual ability yield an overall or full-scale intelligence score. This full-scale score reflects *g*. Several measures, the Wechsler scales in particular, yield separate performance and verbal scale measures. Carroll suggests that the performance scales are related to general visualization (*Gv*) more than *Gf* as is commonly interpreted. The verbal scales are thought to reflect *Gc*.

Summary

There is considerable consensus that the original formulation of Spearman of a general factor of intelligence, *g*, provides a useful descriptive account of individual differences in cognitive ability. Cattell's distinction of separate *Gf* and *Gc* factors has been incorporated into many studies and models of intelligence. It appears that there is a considerable relation between the two constructs of *Gf* and *g*. In particular there is a claim by Gustafsson (1984) that these constructs may be identical. At the present time, it is difficult to utilize this descriptive structure of intellect in experimental work. There is no one instrument that adequately assesses intelligence in these second-order dimensions. Therefore, there is reliance on particular markers of the factors. Due to this constraint, it is more practical to attempt to evaluate *g*, *Gf*, and *Gc* since they account for the largest portion of variability in intelligence. In the present thesis, the Multidimensional Aptitude Battery (MAB) is used to evaluate cognitive ability. This battery yields separate scores for verbal, performance, and full-scale IQ. The full-scale score will be used as a marker of *g* and the verbal IQ score will

be related to G_c . The performance score as discussed above may be related to either G_f or G_v . In either case the MAB provides indications of psychometric g , G_c , and either G_f or G_v .

Heredity and Environment

Biometric methods have been developed to assess the relative contribution of hereditary and environmental influences on individual differences in psychometric intelligence. In the first part of this section, the heritability of intelligence as assessed by quantitative methods will be reviewed. This was one of the first areas of intelligence to be investigated (Galton, 1869) and it continues to receive attention in experimental work. The next section reviews attempts to improve intellectual functioning. This work has developed primarily from the perspective that levels of intellectual ability are influenced by one's environment. The largest portion of this work is from studies attempting to improve intellectual performance of disadvantaged children by providing some form of enrichment.

Quantitative Genetic Analysis of Intelligence

Heritability of intelligence has been a highly debated topic in the past century. Heritability is a technical term used in quantitative genetic research to indicate the amount of total variability in a measure that can be accounted for by genetic variation. The assessment of heritability involves the partitioning of variance of intelligence tests into portions related to genetic or environmental components. The partitioning of variance is accomplished by assessing intelligence for pairs of individuals in whom genetic relatedness is known and in whom common environmental similarity can be determined. Estimates of genetic relatedness are established by using family resemblance as a guide. For instance, identical twins share

100% of their genes while fraternal twins share only 50% of their genes. Shared and unshared environmental variability is assessed by using individuals that grow up in the same family compared to those who for one reason or another (such as adoption) are raised in separate settings. It must be stressed that the process of partitioning variance applies to populations and the sample tested is expected to represent the general population. Therefore, heritability estimates do not relate to particular individuals. They can only be meaningfully discussed in reference to the population on which the measurements were taken. In addition, heritability estimates, because they are population statistics, may differ between populations. Estimates of heritability must be used with appropriate caution.

It is of interest to know if intelligence is heritable for several reasons. The development and potential success of programs aimed at raising intelligence uses knowledge of the determinants of intelligence. If the determinants are environmental in origin, remediation of adverse environmental conditions may provide a useful means to improve intelligence. However, if it appears that variability in intelligence is primarily related to genetic variation, then interventions aimed at improving environmental effects may be expected to have only limited effects. Knowledge of the heritability of intelligence is also useful as a rough guide for research. A genetic influence would suggest a path of investigation into biological correlates of intelligence. Likewise, the relative importance of shared and unshared environmental variation can be used as a guide for areas of investigation. A comprehensive theory of intelligence should also account for the sources of variation in biometric studies of intelligence.

One of the earliest methods devised for the assessment of heritability involved the

comparison of identical and fraternal twins. Identical twins have the same genetic constitution and therefore, differences between identical twins can only be due to environmental differences. Fraternal twins have only 50% of their genes in common. An early method of estimating heritability was to double the difference in intra-pair correlations between identical and fraternal twins. However, since twins share the same environment, differences due to the shared environment may not be evident. One way to control for this effect is to compare identical and fraternal twins that were raised apart to twins that were raised together. Identical twins may be treated more similarly than fraternal twins. The inclusion of twins raised apart allows for more accurate assessment of genetic and environmental effects. One other consideration in the early studies was that the determination of a twin pair as identical or fraternal was not always accurate. More recent studies have employed improved techniques for determining twin status. The reports described below will highlight the findings from some of the best controlled studies that have used both twins reared together and twins reared apart.

McGue and Bouchard (1989) presented data collected as part of the Minnesota Study of Twins Reared Apart that are particularly relevant (Bouchard, 1984, 1987). This study used 49 sets of identical twins reared apart and 25 pairs of fraternal twins reared apart. They assessed heritability of Verbal reasoning, Spatial ability, Perceptual speed, and Visual memory factors. The Spatial ability factor showed the highest estimate of heritability at 71% while verbal reasoning and perceptual speed had heritability estimates of 57% and 53% respectively. Heritability of the Visual memory factor was lower and an estimate was not given for this factor.

In another twin study, the Swedish Adoption/Twin Study of Aging, estimates of heritability were calculated from correlations of identical and fraternal twins raised together and apart (Pedersen, Plomin, Nesselroade, & McClearn, 1992). There were 46 identical and 100 fraternal twin pairs raised apart. In addition, 67 identical and 89 fraternal twins raised together were used. Measurements in this study were conducted when the subjects were an average of 65 years of age. This is in contrast to other studies that have used younger subjects. This arrangement allowed for the estimation of additive and non-additive genetic influence and also separate estimation of the shared and unshared portions of variation associated with environment effects. A measure of *g* was estimated to have a heritability of 81%, which includes both additive and non-additive sources of variance. *Gc* and Perceptual speed abilities were estimated to have an average heritability of 58%. *Gf* and Memory tests were less heritable (46% and 38% respectively). The assessment of variability due to environmental effects revealed that the source of variance associated with shared environment has little impact on these measures of intellectual performance.

Substantial estimates of the heritability of intelligence have also been found using both family studies (e.g. Teasdale and Owen, 1984) and adoption designs (e.g. Cardon, DiLalla, Plomin, DeFries, & Fulker, 1990). Estimates from these sources have tended to be somewhat smaller in magnitude than those reported in the more recent twin studies.

Summary of heritability

It appears that about 50 - 80% of the variability in cognitive abilities is accounted for by variation due to genetic sources. This also allows for a portion of variance that is attributable to environmental factors. Heritability estimates vary according to the type of

sample studied, the type of intellectual ability being assessed, and the age of the sample (Bouchard, Lykken, McGue, Segal, & Tellegen, 1990; McGue, Bouchard, Lykken, & Feuer, 1984). There is considerable evidence that the shared environment (that which makes children growing up in the same home similar) has little effect on intelligence that is evident after early childhood.

Malleability of Intelligence

Although changes can occur in abilities over the life-span, it is generally agreed that intelligence is a relatively stable and enduring trait. While there is general agreement on the relative stability of intelligence, a goal of many researchers is to reveal how cognitive ability can be enhanced. The first part of this section will review attempts to improve cognitive ability through intervention programs. This topic has received much attention. The emphasis of this work is on providing enrichment to the severely disadvantaged or those deemed at risk for mental retardation. Intervention studies have focused on the enrichment of the early experiences of children and providing them with sufficient tools to be more successful in school. Evidence for the malleability of intellectual abilities can also be obtained indirectly from sources such as adoption studies. Adoption studies lend insights into how an enriched environment affects intellectual ability compared to a relatively impoverished setting.

The first major report of an intervention aimed at improving cognitive ability was reported in 1946 (Schmidt, 1946, cited in Locurto, 1991). This study reported the progress of 254 adolescents who were given 3 years of training. At the beginning of the training period, the average IQ was 52. By the end of the program the average IQ was up to 72. Five years after the program was completed, the IQ average was reported to be 89. The results of

this study are somewhat clouded by the refusal of the author to allow others to examine her data.

A multitude of intervention programs were started in the early 1960s under the auspices of Head Start, a program in the US to help disadvantaged youth prepare for entry to school. Early results of these programs were discussed at length in "How much can we boost IQ and scholastic achievement?" by Jensen in 1969. These studies indicated that gains in intelligence scores disappeared soon after the completion of the preschool program. A meta-analysis by the Head Start Bureau (1985) containing 72 separate evaluations concluded that gains were generally reported at the end of the training period. However, the intelligence score gains were no longer evident three years after the intervention programs had terminated.

A group representing eleven separate intervention projects that were conducted in the 1960s joined forces to do a long-term follow-up of the progress of the individuals in their programs (Lazar & Darlington, 1982). The results of this follow-up confirmed the findings in the meta-analysis of Head Start Bureau. Gains observed in intelligence scores at the end of the intervention program were no longer evident approximately three years after the program ended. The long-term follow-up showed that there were still no differences in intelligence between those in the intervention programs and those in the control groups. A problem for these studies was that the assignment to control groups was not randomized. The general strategy was that those with visible needs were selected for the intervention program. The control group consisted of others in the community. The Perry Preschool Project was unique in this regard in that random assignment to a control group did occur. However, a similar

pattern was observed in the results of this intervention. A 10-point IQ gain at the end of the study disappeared completely by age 14.

The Milwaukee Project (Garber, 1988) is notable for its exceptional length of intervention and results. The intervention started at 3 months of age and continued to school age. Extensive interventions were designed for both child and parent. The exceptional result of this study was that enduring differences in IQ were reported. At the end of the intervention, a gain of 20 IQ points was noted. At age 12 to 14 a 10-point IQ gain remained. The results published from this project were challenged. The intervention procedures were not described and the head of the project was convicted of embezzling project funds. While both the Schmidt study and the Milwaukee Project have been criticized, they are the only studies to report enduring changes in intelligence.

Intervention programs are designed to prepare students to enter school. It is possible that the problem faced by the student is a product of the community. If this is the case, intervention programs would not be addressing the proper issue. However, if differences in the environment can affect IQ, then this would suggest that intelligence is malleable. To assess differences due to these environmental sources, adoption study designs are particularly helpful. For the purpose of assessing differences due to the effects of different environments using adoption studies, intelligence of the people adopted into another (enriched) environment is contrasted with intelligence of those who remain in the same (deprived) environment. In some instances, there are also comparisons of those that are adopted from enriched environments into deprived environments.

A few adoption studies have shown that differences in environments between adopted

and biological families may be associated with differences in abilities. Skodak and Skeels (1949) reported a 21-point increase in IQ of the adopted child over the biological parent. Biological parents in this study had an average IQ of 86. The adopted children had an average IQ of 107. There is no direct evidence that the difference is attributable to the effects of an enriched environment. The enriched environment is estimated from the educational level of the adopting families. Some of the difference may be expected due to the operation of regression toward the mean. However, the magnitude of this effect is larger than that predicted by regression to the mean. One problem in this study (and other adoption studies) is that children placed for adoption may be higher in ability than those not accepted for adoption. Low ability children may not be eligible for placement by agencies if they are anticipated to be at risk for mental retardation.

Another example of an adoption study revealing information regarding the malleability of IQ is the French Cross-Fostering Study (Capron & Duyme, 1989). Children from extreme high and extreme low SES families were adopted into families of extreme high or extreme low SES. Despite the status of the biological parents, there was a 12-point advantage in IQ for those adopted into a high SES family (IQ=112) than those adopted into a low SES family (IQ=100). These adoption studies suggest that there is a portion of intellectual ability that is malleable. It must be emphasized that the differences between these extreme groups may not be consistently observed across all levels. Locurto (1991) has suggested that the changes in IQ with SES may not be linear. Instead, he suggests that differences are greater at the extremes than across the normal range of ability and SES. The French Cross-Fostering Study provided the clearest evidence for the malleability of IQ.

Overall, intervention programs appear to have had little success in attaining lasting gains in IQ. There are some exceptions but the most reliable evidence indicates that gains observed during the intervention program disappear in the years following the completion of the intervention. The intervention programs provide relatively short-term enrichment and return the child to their former environment. Evidence from the adoption studies however, suggest that enriched environments may be responsible for more enduring increases in performance on tests of intellectual ability.

Clearly, a large portion of variance in cognitive ability can be attributed to genetic variation. This suggests that there are biological correlates of psychometric intelligence. One of the earliest attempts to relate biological determined measures to intellectual performance was Spearman's use of reaction time in simple cognitive tasks as a measure of cognitive ability. There have been substantial improvements in both psychometric testing and reaction time recording since the time of Spearman. The present thesis expands upon improvements in these areas and combines the use of reaction time measures in simple cognitive tasks with concurrent recording of EPs as a reflection of the biological basis of psychometric intelligence. Since reaction time measures in simple tasks are thought to reflect speed of processing and psychometric testing stresses evaluation of higher cognitive processes, the differences between these approaches will be discussed.

Speed and Power

Most tests of cognitive ability consist of items that increase in difficulty as the test progresses. Scores of ability from this type of test reflect the total number of correct responses. Power is a term used to describe the approach to evaluating cognitive ability that

emphasizes the level of difficulty a subject can master. Power is sometimes contrasted with measures emphasizing the speed with which cognitive tasks are performed.

Because most tests of ability have time constraints, psychometric tests of intelligence may be measuring aspects of both speed and power. It has been shown that, within limits, correlations between scores on timed and untimed administrations of the same intelligence test are highly correlated (May, 1921; Ruch & Koerth, 1923; Vernon, P.A. & Kantor, 1986). This however, does not indicate that speed and power scores are identical. The correlations between administrations of similar tests represent part-whole correlations. This tends to overestimate the actual correlation. The scores for both the speed and power measures are in terms of the number correct. Scoring in this way may be producing two alternative power measures rather than one speed measure and one power measure. Speed is more appropriately measured by the amount of time required to complete a particular problem rather than using an accuracy criterion. Therefore, caution must be exerted in interpreting timed tests as measures of speed.

As may be evident, pure measures of power involve the presentation of several levels of difficulty. The measure of interest for power is the maximum level of difficulty that the individual can consistently answer correctly. Measures of speed require special characteristics that may not apply to measures of power. Early studies examining the relation between intelligence and speed of response in simple reaction time experiments used very few trials (Sharp, 1899; Wissler, 1901). It was found that the reliability of these measures increased with a larger number of trials. This allowed for a more realistic appraisal of this work (Spearman, 1904). Pure measures of speed should reflect only those trials in which a correct

response has been made. Important information may be available from error trials and the number of error trials. In general, the information of importance is the speed of correct information processing and not the speed of errors. The number of errors committed in a session yields interesting information regarding the use of strategies, attention to the task, etc. While the information about errors cannot be ignored, the measure of speed should not reflect the speed of incorrect responses. Although both speed and power can be involved in measures of ability, pure measures of speed and pure measures of power are evaluated by different methods.

Speed and power may differ from one another due to differences in methods of measurement rather than representing different aspects of intellectual ability. If pure measures of speed and power reflect common intellectual mechanisms, there should be substantial correlations between these measures on similar tests. However, there is some evidence that indicates that speed and power are relatively independent. The factor analysis of several measures of speed and power on tests of intelligence have suggested that speed and power dimensions are uncorrelated (Porebski, 1954; 1960). This problem has not received much attention recently.

In the extensive factor analytic survey of the cognitive ability literature, Carroll (1993) identifies two general second-order factors related to speed. Carroll suggests the existence of a factor of general speed that includes the rate of test-taking and numerical facility among other comparable factors. Speed of processing in simple reaction time tasks, also forms a distinct second-order factor. Carroll states that this factor "has minimal cognitive content and should not [be] taken to be a cognitive ability" (Carroll, 1993, pp.

625). This view seems contrary to the evidence cited in his reanalysis of the reaction time studies. His reanalysis of 39 independent studies indicates that the general reaction time speed factor is related to psychometric measures of intelligence. The relation of these speed measures with intelligence occurs at a general (second or third-order) level but not at a first-order level. This indicates that speed is related to Gf and g. It is clear from this psychometric analysis that speed is an important part of intelligence.

Reaction Time as a Measure of Speed

Most of the data analyzed by Carroll were primarily based on measures of power. The greater consideration of power is due to the existence of a large body of literature that has been reviewed earlier in the section dealing with the structure of intelligence. This probably stems from the early success of measuring intelligence using measures of power and the subsequent development of tests based on these methods (Binet, 1911; Binet & Simon, 1905). The most frequently employed measure of speed is reaction time (the time from stimulus onset until behavioral response is completed). Some early investigations of intelligence using reaction time measures found them of little value (Sharp, 1899; Wissler, 1901). The use of reaction time in investigations of intelligence has been aided by recent developments in recording and methodology. There is now an extensive literature that has investigated the relation between speed of performance defined by reaction time in very simple tasks and intelligence.

The relation between reaction time and intelligence has been extensively explored using the Hick paradigm. These studies were conducted using a special apparatus introduced by Jensen (Jensen & Munro, 1979). Specifically, a series of eight lights is arranged in a

semi-circle with a response button located below each light. An additional home button is located in the middle of the display. The subject is instructed to keep the home button pressed until the onset of a light. Once a light is illuminated, the subject depresses the response button next to the light. Two measures are derived from this task: reaction time (RT), the time from the onset of the light until the release of the home button and movement time (MT), the time required to move from the home button to the target button. The number of lights visible on a particular set of trials is controlled by placing an overlay on the response box. Several sets of trials are completed with different numbers of lights. RT has been found to increase proportionately with the amount of information contained in the stimulus (the number of lights in the display). MT, on the other hand, is relatively unaffected by increases in the amount of information (Jensen, 1987).

Analysis of the Hick paradigm has involved several parameters derived from RT and MT. In addition to simple means and median values for the set sizes, Jensen has also analyzed the within-subject standard deviation in reaction time (RTsd). In a meta-analysis of over 30 studies, Jensen (1987) indicates that RT, MT, and RTsd are negatively correlated with intelligence. The level of correlations in these studies averages $-.31$, $-.29$, and $-.32$ for RT, MT, and RTsd respectively. The results of these investigations give strong support to the view that speed, independent of power, contributes substantially to variation in intelligence.

Another experimental procedure, the inspection time (IT) paradigm, has also received a good deal of attention (Vickers, Nettelbeck, & Wilson, 1972). IT has been defined as the minimum exposure time needed to identify a particular feature of a stimulus. The original

inspection time task involved discriminating which of two vertical lines were longer. The exposure duration for the lines was systematically varied in order to estimate the shortest duration at which a particular level of accuracy is attained. Each presentation of the inspection stimulus was followed by a mask. It was found that even mentally retarded individuals could perform the task accurately with an exposure time of less than 10 ms when the mask was not used (Nettelbeck & McLean, 1984). Two independent meta-analyses of the literature on IT reported an average correlation of IT with intelligence of about $-.50$ (Kranzler & Jensen, 1989; Nettelbeck, 1987). There have been other variants of IT including variations of the visual tasks and tasks using auditory and tactile sensory stimuli.

The pattern of correlations of IT with various measures of intelligence is summarized in the two meta analyses. In general, verbal measures of intelligence are poorly related to IT while performance measures (which Carroll suggests are closer to a general visualization factor) are more strongly related to IT. Most studies do not include extensive psychometric batteries that would allow a definitive pattern of relation of inspection time to g .

The term elementary cognitive tasks (ECTs) refers to a variety of reaction time tasks that are used to investigate the relation between specific cognitive processes and intelligence. Several tasks have been devised that putatively reflect different aspects or stages of information processing. These tasks provide measures of the speed of short-term memory scanning, retrieval from long-term memory, visual scanning, speed of lexical access, and semantic access among others.

Two of the most widely used tasks are the Sternberg memory scanning task (Sternberg, S., 1966) and the letter matching task introduced by Posner, Boies, Eichelman,

and Taylor (1969). The Sternberg task involves the presentation of a set of items to memorize followed by a test item. The subject indicates if the test item was one of the items from the memory set. The Sternberg task is used as a method of evaluating processes related to short-term memory access.

The Posner letter task involves the comparison of two separate tasks. In the first phase, a pair of letters is displayed (e.g. "Aa" or "AA") to which the subject determines whether the letters are physically identical. The second task requires a response that is based on name identity (e.g. "AA" and "Aa" are similar while "Ab" and "Ba" are not similar). The difference in latency between the two tasks is thought to index the time required to access the names from long-term memory. These are examples of a wide variety of tasks that have been exploited in research into the nature of cognitive abilities.

While ECTs represent a wide array of cognitive concepts, they all have certain features in common. Generally, the dependent measures in these tasks are measures of speed of processing. ECTs are relatively simple in nature. Error rates are relatively low for most subjects (although problems may arise in mentally retarded subjects). The level of difficulty may vary among tests, but quite often difficulty is not manipulated within a particular ECT. These features make ECTs ideally suited for reaction time studies of the speed of processing and intelligence.

Several studies have reported significant correlations between first principle component scores of intelligence batteries and reaction time batteries (Kranzler & Jensen, 1991; McGarry-Roberts, Stelmack, & Campbell, 1992; Miller & Vernon, P.A., 1992; Vernon, P.A., 1983). The first principal component of these batteries reflects the common

variance shared by all tests in the analysis. In this respect, the first principal component is analogous to the type of factor derived by Spearman in assessing *g*. The significant correlation between what is common to the tests of intelligence and what is common to the reaction time test battery implies that there may be a significant relation between speed of processing and *g*. In general, these studies have demonstrated correlations between the general reaction time factor and *g* of $-.30$ to $-.40$.

In summary, speed and power have been investigated in a number of separate studies. The traditional approach to the investigation of intelligence has utilized power measures. Our knowledge about the structure of intelligence has almost entirely been derived from power measures. However, considerable evidence indicates that speed of processing is related to *g*. The correlation appears to be moderate, approximately $-.35$ between speed of processing and psychometric (power) measures of intelligence. This level of correlation may be attenuated due to variability that can be attributed to differences in the method of measurement. There may be variability in reaction time data that is due to the measure itself that is not related to intelligence. It is well established that differences in the utilization of strategies produce substantial changes in overall reaction time (e.g. speed-accuracy trade-off, Houlihan et al., in press). The use of other measures of the speed of processing such as event-related potentials (ERPs) may eliminate some of the method variance associated with reaction time measures and produce larger correlations with intelligence. Speed and power measures appear to contribute unique information about the overall nature of intelligence. Speed of processing and more traditional psychometric evaluations of intelligence will be compared. Speed of processing will be evaluated using measures of RT, and MT during the performance of

ECTs. In addition, ERPs will be recorded concurrent with the performance of these tasks and the latency of P300 component will be used as an additional index of speed of processing.

Biological Correlates of Intelligence

Evidence cited earlier regarding the heritability and malleability of intelligence suggests that 50% to 80% of the variability in intelligence is associated with genetic variation. From this evidence, it follows that the portion of cognitive ability that can be explained in terms of genetic variance will manifest itself in or be correlated with biological characteristics that are also genetically determined. The idea that there is a relation between physical and mental abilities has been around for a long time. However, scientific investigation into the relation between intelligence and other biological characteristics is relatively new. Several biological characteristics have received a sufficient amount of investigation to consider. These have demonstrated consistent correlations with intelligence in several studies and with different investigators. However, the functional relation between some of these measures and intelligence is uncertain.

There are several possible explanations for relations between physical and mental traits. Jensen and Sinha (1993) suggested that correlations could result from short-term environmental influences such as nutrition, or as a result of cross-assortive mating on the basis of the two traits. In addition, they suggest that the appearance of correlations between intelligence and physical traits could "be the result of a long evolutionary process involving the natural selection of genetically conditioned coadapted traits" (Jensen & Sinha, 1993, pp.143). This final suggestion gains support from quantitative genetics that indicate a substantial heritability for intelligence.

One biologically determined characteristic that has been consistently related to IQ is physical height. Height is positively correlated with intelligence. Jensen and Sinha (1993) reviewed recent studies reporting correlations of .12 to .29 (n-weighted mean .23) for samples of 203 to 7500 subjects. As stated previously, it is plausible that the correlation between height and intelligence is mediated by differences in nutrition. However, controlling for differences in socioeconomic status did not affect the correlation in these studies. Another large scale study (n=43,979) examined Danish military recruits (Teasdale, Sorenson, & Owen, 1989). This study confirmed the finding of Jensen and Sinha (1993). While the correlations between height and intelligence are low, the effect is significant in several studies suggesting that taller individuals have higher intelligence scores.

The long standing claims of a relation between head size and cognitive ability is thought to be incredulous. However, there is evidence suggesting larger brain size is associated with higher levels of intelligence. Correlations between head size and WISC IQ of .24 and .18 were reported for white and black groups respectively in a large scale study of 36,000 7-year-old children (Broman, Nichols, Shaughnessy, & Kennedy, 1987). Another large scale study by Sausanne (1979) found a correlation of .24 between head size and cognitive ability in 2000 Belgian males. Rushton (1992) also found significant correlations between head size and IQ for Orientals ($r = 0.14$) and whites ($r = 0.21$).

New technology has been applied to the question of a relation between brain size and intelligence. This new source of information comes from the use of magnetic resonance imaging (MRI) techniques. The use of MRI avoids the problems associated with estimates of brain size based on measures of the volume of the head (either from external measurement or

from autopsy data). Willerman, Schultz, Rutledge, and Bigler (1991) found that MRI based estimates of head size correlated .65 with intelligence in males and .35 in females. These correlations may be slightly overestimated due to the use of extreme IQ groups. Another MRI study using 29 subjects, found that Gf was correlated .43 with brain size but Gc was uncorrelated with brain size (Raz et al., 1993). The difference in size between left and right hemispheres was correlated with both Gf ($r = .46$) and Gc ($r = .62$).

Except for the MRI studies, correlations of head size with cognitive abilities are based on large samples. While the estimates of head size from external measures of the head may be unreliable, the numerous replications in these large samples of the positive correlation suggest that a stable relation exists. The technological advance in MRI avoids the problem of inaccuracy of measurement of brain size and may improve the reliability of brain size measures. In addition to estimating total brain size, MRI can be used to measure individual structure that may account for the correlation with intelligence. The MRI results, which suggest a substantial correlation between brain size and intelligence, require replication if they are to continue to be useful.

Nerve conduction velocity (NCV) is also correlated with intelligence and is considered to reflect speed of neural transmission directly. In the NCV procedure, the median nerve is stimulated by an electrical pulse. The time between the action potentials recorded from two sites along the neural pathway is used to calculate the speed of neural transmission. Temperature is controlled in order to reduce unrelated individual differences. P.A. Vernon and Mori (1992) found correlations of .42 and .48 between NCV and intelligence scores in two independent studies. However, there have been several unsuccessful attempts to replicate

this effect (Barrett & Eysenck, 1993; Barrett, Daum, & Eysenck, 1990; Reed & Jensen, 1991; 1992). Barrett and colleagues found that variability in NCV was correlated with intelligence but NCV was not correlated with intelligence (Barrett & Eysenck, 1993; Barrett et al., 1990). Methods used in these studies varied considerably. Methods for controlling for differences in body temperature, length measured, and location of measurement varied among studies. It is too early to make definitive statements about the relation between NCV and intelligence. Since the methods of measuring NCV in vivo are not well established, this work will require further refinement in order to determine the true relation between NCV and intelligence.

Positron emission tomography (PET) provides a measure of brain activity by tracing the amount of radioactive glucose taken up in areas of the brain. Two early studies that employed this technique found that lower mental ability was associated with low rates of glucose utilization (Chase et al., 1984; de Leon et al., 1983). These studies recorded brain glucose utilization during a period of rest. De Leon et al. (1983) contrasted normal elderly subjects with those with senile dementia. The study of Chase et al. (1984) found a correlation of .68 between total glucose uptake and full-scale IQ from the WAIS in a mixed group of normal subjects and Alzheimer patients. Chase et al. (1984) also reported the highest correlations of the verbal IQ scores with regional glucose uptake rates from the left hemisphere while the performance scale IQ measures correlated highest with right hemisphere glucose utilization. These studies are in agreement with one another but are based on data from very few subjects and have relied on the use of clinical groups. A stronger case could be made from these studies had larger samples and normal populations

been used. However, these two studies suggest that when subjects are at rest, brain metabolism is positively correlated with intelligence.

A different relation between glucose uptake and intelligence appears when subjects complete cognitive tasks than when subjects are at rest during the uptake period. Haier et al. (1988) had subjects complete the Ravens Advanced Progressive Matrices (RAPM) during glucose uptake. RAPM performance was negatively correlated with glucose metabolic rates. In another study, a verbal fluency test was completed during glucose uptake (Parks et al., 1988). Brain activity was correlated $-.54$ with verbal fluency performance scores. It appears from these studies that the relation of brain activity to intelligence depends upon the conditions under which the measurement of activity is recorded. Overall glucose uptake was positively correlated with intelligence when a novel visuospatial task was completed during the uptake period in a small sample of male subjects (Haier, Siegel, Tang, Abel, & Buschbaum, 1992). The correlations between cognitive ability and global glucose uptake disappeared after practice on the task. Positive correlations between PET activity and intelligence have been found when subjects were at rest during the uptake period. However, when subjects are required to complete tests of cognitive ability during the uptake period, the relation between glucose uptake and intelligence is negative. Haier explained these results in terms of the efficient use of processing resources. While providing valuable information about brain activity, the disadvantages of PET methods are that they are expensive, invasive, and lack temporal resolution of brain function. The technique provides a good measure of brain activity that allows for a degree of localization of function. In this regard PET recording may become a valuable tool for investigation of individual differences in cognitive

ability.

Summary

Both brain size and height are known to be determined primarily by genetic processes. Both of these measures are positively correlated with intelligence. The correlations are low but consistent. The use of MRI techniques to relate brain size to intelligence have resulted in larger correlations between intelligence and brain size, especially for Gf. While there is little doubt that these relations exist, the functional relation between either brain size or height and intelligence is not clear.

The relation between NCV and intelligence is built on the premise that more efficient information processing is faster than inefficient processing. The evidence cited above reveals serious inconsistencies across studies. However, this work is in its infancy and much is left for further investigations to reveal.

PET methods are flexible in that they allow the assessment of brain activity during qualitatively different cognitive tasks. This allows for examination of the functional significance of particular activities on the relation between brain activity and intelligence. It is evident from the review that the direction of correlation between intelligence and glucose uptake is greatly affected by processing demands during the uptake period. During difficult tasks higher intelligence is associated with lower levels of brain activity. This is a relatively new approach to the study of cognitive ability and there are only a few relevant studies using very small sample sizes. The lack of temporal resolution in PET recordings may limit the effectiveness of this procedure in investigating the nature of cognitive abilities. An alternative to the invasive and costly PET procedures for assessing brain function is the use of EPs. In

addition to being more cost effective and less invasive the temporal resolution of EPs is much greater than that in PET activity.

Intelligence and EPs

Evoked-potentials (EPs) are scalp recorded voltage changes in response to specific physical stimuli or psychological events (ERPs). EPs reflect neural activity that is time locked to a stimulus presentation or a psychological event. They also allow for the analysis of changes in activity with a temporal resolution in milliseconds rather than over a longer period as with PET recorded activity or functional MRI. The use of EPs in research into intelligence has stemmed from two main sources. It is implicit in most of the research investigating the relation between EPs and intelligence that efficient neural activity describes the higher intelligence subject. There have been several attempts to quantify efficiency using measures derived from EPs. The second source of relation between EPs and intelligence is derived from the fact that EPs provide good temporal resolution regarding the timing of cognitive events. In particular the latency of the P300 component is useful as a measure of stimulus evaluation time and is relatively independent of response processes. The greater temporal resolution allows for the analysis of the relation between speed of processing and intelligence. A historical review of the use of EPs and ERPs in research on intelligence will be followed by a more detailed analysis of those studies focussing on the relation between intelligence and ERPs during simple cognitive tasks.

Historical Overview: EPs, ERPs, and Intelligence

The use of evoked-potentials (EPs) in research on intelligence can be traced to origins at the University of Ottawa (Chalke & Ertl, 1965; Barry & Ertl, 1966; Ertl, 1969; Ertl &

Schafer, 1969). This work generated a great deal of controversy. Ertl and his colleagues, attempted to measure the speed of processing of simple visual information. Ertl's montage consisted of a bipolar recording over the right hemisphere (3cm anterior and posterior respectively from C4 of the international 10-20 system). This montage "...was chosen with the idea of maximizing the input-output delay and thus to enhance the possibility of actually measuring central processing time." (Chalke & Ertl, 1965, pp. 1320). The early work by Ertl and his colleagues showed that the latency of the third peak of EPs to light flashes was highly correlated with intelligence scores on standard psychometric tests. Correlations were reported as high as -.78. Considering the reliability of the EP and IQ measures, this would indicate a relation that was near unity. Because of the excitement generated by these results, large scale replications were started almost immediately. Ertl also began marketing a Neural Efficiency Analyzer for measuring intelligence using the methods described above.

The most comprehensive attempt at replication of Ertl's experimental work was completed by Davis (1971). He tested over one thousand children and went to great lengths to duplicate the procedures and efforts of Ertl. In order to ensure that the methodology was duplicated, Ertl served as a consultant on this project. The results failed to reveal a relation between the latency measures and intelligence. Ertl's Neural Efficiency Analyzer was evaluated by Everhart, China, and Auger (1974). They reported correlations from small samples of subjects that ranged from +.54 to -.50 for various sub-tests of the WAIS. However, there were other studies that reported findings that were similar to those reported by Ertl (Callaway, 1975; Shucard & Horn, 1972; Gucker, 1973). For example, Plum (1968) used similar methods but varied the electrode montage slightly and obtained correlations of

peak latency that ranged from -0.21 to -0.29. Overall, using the methods and montage devised by Ertl, these studies reported an average correlation of approximately -.30 between peak latency and intelligence.

While there seems to be evidence of a consistent pattern of correlations between peak latency and intelligence, the evidence from the Ertl design has been criticized on several grounds. a) Little experimental work was published regarding the functional significance or validity of this EP method as a measure of input-output delay or central processing time. b) There was little control over eye fixation or concerns about eye movement or other artifact. c) Since subjects are passive during the recording epoch, there is no way of ascertaining what the subject was doing during the recording. d) The most serious criticism of Ertl's methodology was in the identification of peaks. The first identifiable peak in any record was identified as peak 1 the second as peak 2, etc. regardless of the latency of the peak. In this system, records with a large number of peaks will tend to have smaller latency associated with each peak. Peak 1 in one person's record may correspond to peak 3 in another person's record that has a larger number of peaks. Ertl also used a zero crossing analysis for the identification of peaks in his studies. This technique has not been continued and its validity is questionable. e) Although it is not clear in all studies, the latency measures may have been determined directly from the zero crossing analysis rather than from peaks of the EP. There is speculation that this measure reflects background EEG frequency rather than peak EP latency (Everhart et al., 1974).

Hendrickson (1972) noted that the EPs of higher IQ subjects in Ertl's reports were characterized by greater complexity. Hendrickson devised the string measure, the length of

the contour of the EP waveform, to capture this complexity. This measure is quantified by the sum of squared differences between adjacent amplitudes. The string measure was first applied to the selected EPs published in an article by Ertl and Schafer (1969) and this resulted in a correlation of .77 between the string measure and intelligence. Hendrickson (1982) then collected EPs to 1000Hz, 85db tones presented randomly (1 - 8 s between tones). He reported correlations between string and intelligence of 0.68, 0.53 and 0.72 for WAIS verbal, performance, and full-scale scores respectively. Blinkhorn and Hendrickson (1982) found that the string measure was correlated with the Ravens (a measure of Gf) but was not related to verbal abilities. Other successful replications of the relation between string and intelligence were reported (Gilbert, Johnson, Gilbert, & McColloch, 1991; Haier, Robinson, Braden, & Williams, 1983; Rhodes, Dustman, & Beck 1969; Stough, Nettelbeck, & Cooper, 1990). However, there have been notable failures to obtain these results and in some instances, there were reports of correlations in the opposite direction (Barrett & Eysenck, 1992; Bates & Eysenck, 1993; Shagass, Roemer, Straumanis, & Josiassen, 1981).

Once again, there is little known about the functional or theoretical significance of the string measure. Differences in string measures may be due to a host of variables that may be only tangentially related to intelligence. For instance, individual differences may be due to muscle artifacts. Similar to the criticism of Ertl's work, there is no control over the cognitive state of the individual. The subject is passive and there is no way to confirm that the subject was attentive. Interpretation of the functional significance of the string measure is more difficult due to the observation of both positive and negative correlations with intelligence.

These studies have focused on the analysis of neural responses evoked by simple

sensory stimuli in which the subject is passive. They are of particular interest because of the very large correlations reported, especially in early studies. These investigations employed non-standard EP measures and methods in comparison to recent research. In the following section, studies that have used more conventional methods and measures (i.e. latency and amplitude of particular peaks) are reviewed. Once again these studies focused on the EP from simple visual flashes or auditory tones and in a few instances somatosensory stimuli were employed.

In general, early sensory evoked responses are considered to be exogenous in nature, that is, variation in EPs is mainly due to changes in the physical parameters of the evoking stimulus. However, some later components (such as P200 and P300) are considered to be endogenous. The variation in endogenous component amplitude or latency may be due to psychological events unrelated to physical qualities of the eliciting stimulus. The relation between intelligence and these later components shall be considered separately.

Early EP Peaks

Several studies indicated that larger EP amplitude of the exogenous components is related to higher intelligence (Callaway & Halliday, 1973; Haier et al., 1983; Osaka & Osaka, 1980; Rhodes et al., 1969; Shagass et al., 1981). This is exemplified in the studies from Shagass' laboratory (Josiassen, Shagass, Roemer, & Slepner, 1988; Shagass et al., 1981). EPs were recorded to simple auditory, visual, or somatosensory stimuli. The largest correlations were found between intelligence and amplitude to visual stimuli. The correlations with auditory stimuli were positive but small. Contradictory results were reported for somatosensory stimuli. A negative correlation between intelligence and amplitude was found

in the first study and a positive correlation was found in the second.

It is possible that the relation between cognitive ability and EP amplitude may be modulated by stimulus intensity. Haier et al. (1983) reported larger positive correlation between N140-P200 amplitude and intelligence for medium-high intensity light flashes. A recent study found negative correlations between N1-P2 amplitude to auditory clicks (65, 75 and 85 db) and intelligence (Widaman, Carlson, Saetermoe, & Gailbraith, 1993). This particular study found larger correlations for the most intense (85 db) stimuli. However, the bulk of evidence supports the view that EP amplitude to simple sensory stimuli is positively correlated with intelligence. These studies indicate that relatively intense stimuli result in larger correlations with intelligence than relatively weak stimuli.

The relation between the latency of sensory EPs and intelligence is not clear. Some authors have reported faster latency for subjects with higher cognitive abilities (Hendrickson, 1972; Osaka & Osaka, 1980; Rhodes et al., 1969). Shagass et al. (1981) also found faster latency related to higher intelligence for somatosensory EPs but not for auditory or visual EPs. In addition to failures to find a relation between EP latency and intelligence (Engel & Henderson, 1973; Rust, 1975), there have also been findings of faster latency for lower ability subjects (Callaway, 1975; Callaway & Halliday, 1973; Vogel, Kruger, Schait, Schnobel, & Hassling, 1987).

P200

P200 amplitude has generally been positively correlated with intelligence (Callaway & Halliday, 1973; Callaway, 1975; Haier et al., 1983; Josiassen et al, 1988; Osaka & Osaka, 1980; Robinson, Haier, Braden, & Kregel, 1984; Shagass et al, 1981). In the studies that

examined differences in intensity, Haier found that high to moderate intensity flashes resulted in the largest P200 amplitude correlations ($r = +.59$) (Haier et al., 1983). Widaman et al. (1993) found negative N1-P2 correlations with Gc ($r = -.18$ to $-.38$) but not Gf at three levels of intensity for auditory stimuli. However, P2-N2 amplitude was not correlated with scores of either Gf or Gc. The positive correlation with cognitive ability has not always been found (Barrett & Eysenck, 1992; Rust, 1975; Widaman et al., 1993). In one study that used mentally retarded subjects, a negative correlation between P200 amplitude and intelligence was observed (Barnet & Lodge, 1967). Generalizations across studies is difficult because of variation in stimulus and recording parameters. However, most studies indicated a significant positive correlation between intelligence and P200 amplitude.

There have been only a few studies to report significant relations between P200 latency and intelligence. Control subjects had a longer P200 latency than mentally retarded subjects in one study (Vogel et al., 1987). Shagass et al. (1981) also found longer P200 latency to visual stimuli for a high IQ group but did not find differences for auditory or somatosensory stimuli. Callaway noted very small positive correlations between P200 latency and intelligence averaging $+.17$. Several studies have found no relation between P200 latency and intelligence (Barnet & Lodge, 1967; Barrett & Eysenck, 1992; Callaway & Halliday, 1973; Engel & Fay, 1972; Henderson & Engel, 1974; Rust, 1975; Widaman, et al., 1993; Zhang, Caryl, & Deary, 1989a; 1989b).

The EP studies described above have varied in modality, stimulus duration, intensity and frequency. They have also used a wide variety of measures of intelligence. To date the only systematic investigation on the effects of these parameters come from two investigations

on the effect of stimulus intensity (Haier et al., 1983; Widaman et al., 1993). As stated previously these investigations indicated that the largest relation between intelligence and EP measures were obtained at moderate to high intensities. Besides the two studies cited above, there has been little consideration of the effects of stimulus parameters on the correlation of EPs with intelligence. Auditory stimuli of low frequency ($< .5$ Hz) and high intensity (75-85 db SPL) produce EPs with greater between-subject variability than other auditory stimuli (Rothman, 1970). Greater variability in EPs may enhance the possibility of uncovering individual differences in EPs related to intelligence.

In general, there is a good deal of evidence suggesting that larger EP amplitude responses are related to greater ability. These correlations very seldomly exceed .40. Therefore, large sample sizes are required to reliably reproduce these effects. There is relatively little evidence to indicate that EP peak latency is related to intelligence. These results are in contrast with the reports of negative correlations between latency and intelligence from studies using Ertl's methods. For the early exogenous potentials there have been both positive and negative correlations with measures of intelligence. The consistent finding of no correlation between P200 latency and intelligence in these studies should not be surprising. The subject was passive in these studies. There were no controls for the attentional state of the subject which is known to influence the P200. The examination of latency follows from the premise that faster information processing should be associated with higher levels of intelligence. This appears to be questionable from the above evidence. This is particularly evident for the P200 which is at least partially endogenous. It is possible that the relation between processing speed and intelligence may be modulated by psychological

variables. There have been a few studies that have controlled for some of these effects.

Attention and EPs

There have been suggestions that the relation between EPs and intelligence may be affected by attention. The first study that attempted to control attentional modulation recorded EPs during sleep (Barnet & Lodge, 1967). Callaway and his colleagues (1975; Shucard & Callaway, 1974) explored attentional variation more directly. In one condition, subjects attended to either tones or flashes. In another condition, subjects were instructed to ignore the stimuli. However, they found that differences between the attend and ignore conditions were not related to intelligence.

Schafer and colleagues (1979; 1982; 1984; Schafer & Marcus, 1973) proposed that a brain using fewer neurons to process an expected sensory input saves its limited energy and therefore is more efficient. EPs are larger to stimuli that are unexpected than to those that are anticipated. Schafer suggested that those individuals that show larger responses to unexpected stimuli and smaller responses to expected stimuli are more adaptable and therefore are more efficient. Schafer recorded EPs to simple tones in three different conditions in which the knowledge of the occurrence of the stimulus is varied. Random ISI, constant ISI, and subject controlled presentations were used. Schafer employed a highly unusual measure of the evoked potential. He proposed a neural adaptability (NA) measure based on the average amplitude across the complete sweep (500 ms) in the three conditions. NA was defined as the difference between the random and self-administered amplitudes divided by the amplitude in the random condition. (Later studies used the average amplitude of the three conditions as the divisor to compute NA.) Schafer and Marcus (1973) used three

groups of subjects and showed that mentally retarded individuals had smaller NA scores than technicians who in turn had smaller NA scores than PhD. scientists. Jensen, Schafer, and Crinella (1981) reported a correlation of 0.31 between NA and a measure of *g* in a sample of mentally retarded subjects. Schafer (1982) extended this work using normal subjects with mean WAIS score of 118. NA scores correlated .66, .63 and .44 with full-scale, verbal and performance scores respectively from the WAIS. Interestingly, the amplitude in the random condition correlated .65, .61, and .43 with full-scale, verbal and performance measures. This would suggest that the calculation of the difference between random and self-administration conditions does not add significantly to the relation with intelligence over the correlation of the amplitude in the random condition. It is noteworthy that the verbal scores correlate higher with amplitude than performance scores. Callaway (1975) could not replicate the correlations between NA and intelligence. More recently, Barrett & Eysenck (1993, personal communication) also failed to duplicate Schafer's results.

It has been suggested that the relation between NA and intelligence reflects the process of greater habituation in the higher intelligence subjects. Schafer (1984) operationalized habituation as the amount of EP amplitude change between 2 successive blocks of 25 presentations of loud auditory clicks. This index of habituation correlated .59 with full-scale WAIS IQ score. The NA and habituation index together produced a multiple correlation of .64. This demonstrates that there is considerable overlap in the two measures. Schafer's investigation of temporal expectancy and habituation effects can be criticized for similar reasons to both Ertl and Hendrickson. The functional significance and validity of the measures derived from the EP are not established. Despite this criticism, there appears to be

some overlap between the findings from sensory EPs and Schafer's results.

What is the P300?

A wave that develops 300-800 ms after the onset of a stimulus has been referred to as the P300 and is mainly endogenous. (The amplitude and latency of an endogenous component is affected by psychological manipulations such as attention rather than by the physical parameters of the stimulus). A procedure commonly used to elicit the P300 wave is termed the "oddball task." In the oddball task, the P300 component is elicited following the presentation of a rare deviant stimulus in a series of standard stimuli. Variations in P300 amplitude and latency have been observed in a wide range of conditions and experimental paradigms. Experimental manipulations affecting P300 amplitude have been summarized in a model by Johnson (1986; 1988). This model involves three factors. Two independent factors, *subjective probability* and *stimulus meaning*, can be modulated by the third factor of *information transmission*.

With regard to the subjective probability dimension, there is well documented evidence of an inverse relation between P300 amplitude and both stimulus probability and sequential expectancy. In a typical study, a random series of two tones is presented and subjects count one of them (Duncan-Johnson & Donchin, 1977) . P300 amplitude is inversely proportional to the probability of the target tone. In addition to the effects of overall frequency of occurrence, sequential expectancies also affect P300 amplitude. In addition, the immediate repetition of a particular stimulus results in a smaller P300 than when the stimulus was different from the previously displayed stimulus (Squires, Wickens, Squires, & Donchin, 1976).

The stimulus meaning dimension in Johnson's model refers to variation in P300 amplitude that is due to task complexity, stimulus complexity, and stimulus value. Factors affecting this dimension are often referred to in the context of demand for perceptual resources. P300 amplitude becomes larger as task complexity increases. In the standard oddball task, P300 amplitude is larger when a reaction response is required than when the subject merely counts the rare stimuli (Johnson, 1986). Greater stimulus complexity also increases P300 amplitude. For example, P300 amplitude is larger for more intricate patterns (Verbaten, Roelofs, Sjouw, & Slangen, 1986). The final component of this dimension, stimulus meaning, refers to the salience of the stimulus to the subject. This is illustrated in studies that provided subjects with rewards for correct predictions. For example, P300 amplitude was larger following high-risk than low-risk predictions (Johnson, 1979). In each of these examples, the increase in P300 amplitude can be attributed to an increase in the demand for perceptual processing.

The information transmission dimension refers to the discrepancy between the amount of information contained in a stimulus and the amount of information actually processed by the subject. The loss of information is called equivocation. Greater equivocation (loss of information) results in lower P300 amplitude. Manipulations of task difficulty fall into this category. The most extensively studied task in this category is the Sternberg memory scanning task. A variable set of items is memorized and a short time later a single "probe" item is displayed. The subject is asked to indicate if the item was in the memory set. The larger the size of the memory set, the more difficult the discrimination (Houlihan et al., in press). Several studies have shown that P300 amplitude to the probe stimulus is inversely

related to memory set size (Brookhuis et al., 1981; Ford, Pfefferbaum, Tinklenberg, & Kopell, 1982; Houlihan, Campbell, & Stelmack, in press).

P300 latency is important because of its potential as a marker for speed of processing. Peak latency of the P300 component varies from 275 to 700 ms depending on task complexity (Donchin & Coles, 1988). P300 latency is often used as a complement to traditional reaction time measures. P300 latency is largely determined by processes leading up to stimulus classification and is relatively independent of processes related to response production. Support for the independence of P300 latency from response processes has come from several sources. Examples of these sources include the effects of response bias and stimulus discriminability on P300 latency.

The effects of response bias on P300 latency were examined by instructing subjects to emphasize either speed (at a cost of accuracy) or accuracy (at a cost of speed) of responding. Kutas, McCarthy, and Donchin (1977) employed an oddball task using names as stimuli. Speed/accuracy instructions had a large effect on reaction time but little effect on P300 latency. These results have now been replicated in other studies using a variety of experimental tasks (Deacon & Campbell, 1991; Houlihan et al., in press; Pfefferbaum, Ford, Johnson, Wenegret, & Kopell, 1983).

Further support for the independence of P300 latency and reaction time is provided by studies that have manipulated stimulus evaluation processes and response requirements within the same study. McCarthy & Donchin (1981; 1983) (see also Magliero, Bashore, Coles, & Donchin, 1984) varied stimulus discriminability by presenting the word "RIGHT" or "LEFT" embedded in a matrix of letters or a matrix of "#"'s. P300 latency and reaction time were

longer when the word was embedded in the matrix of letters. This suggests that both P300 latency and reaction time were affected by processes related to the discriminability of the target stimulus. Response selection requirements were manipulated by requiring a response that was either compatible or incompatible with the meaning of the word. Reaction time was longer for incompatible responses but P300 latency was not significantly affected by this response selection manipulation. Reaction time was thus influenced by both stimulus classification and response selection. P300 latency was influenced by stimulus classification but not response requirements. Ragot (1984) reported similar results in a spatial compatibility task. Overall, evidence indicates that P300 latency reflects the duration of stimulus evaluation time independent of response processes.

In the present study, P300 latency is employed as a measure of the speed of processing. As reviewed above there is a substantial component of speed related to intelligence. This evidence has been supported by various tasks that have used reaction time as a measure of the speed of processing. Reaction time reflects not only the time required for stimulus evaluation but also includes response related processes that may not necessarily be related to intelligence. Using P300 latency as a reflection of stimulus evaluation time that is relatively independent of response processes may give an additional indication of the relation between speed of cognitive processing and intelligence.

P300 and Intelligence

Several investigators have examined the relation between intelligence and P300 amplitude and latency within the oddball paradigm. P300 latency was measured under two conditions in subjects with dementia (mostly Alzheimer) and control subjects (O'Donnell et

al, 1990). In the first condition, subjects listened to the tones. In the second condition, subjects were asked to maintain a count of the rare deviant stimuli. Patients with dementia had longer P300 latency than control subjects in both conditions. The patient group had lower scores on psychometric tests of cognitive ability than the control group. Furthermore, demented subjects had larger correlations with intelligence in the passive than the counting condition while the reverse pattern was observed in the control subjects. More direct evidence about the relation between intelligence and P300 latency was achieved by adding more control subjects (O'Donnell, Friedman, Swearer, & Drachman, 1992). They found that P300 latency during the passive condition was negatively correlated to factors of verbal learning ($r = -.32$) and verbal fluency ($r = -.39$) using only the normal control subjects. P300 latency from the counting condition was negatively correlated with a factor they identified as intelligence ($r = -.44$) but appears to consist of items related to Gc. P300 latency in the active oddball task was also negatively correlated with a factor labelled "concentration" ($r = -.33$). "Concentration" had major loadings on digit span and mental control tests. However, it is difficult to determine what aspects of intelligence are affected. The factors produced in the analysis are difficult to relate to a particular structure or model of intelligence. In both of these reports, almost all correlations between P300 latency and measures of intelligence are negative. The consistent negative correlation with all measures of cognitive ability may indicate that P300 latency is related to *g*.

Several other studies have found a relation between P300 latency and measures of cognitive functioning when using the oddball task. Negative correlations were found between P300 latency and digit span (Howard & Polich, 1985; Ladish & Polich, 1989; Polich,

Ladish, & Burns, 1990), P300 latency and a global deterioration scale (Polich, Ehlers, Otia, Mandrell, & Bloom, 1986) and P300 latency and self-reported grade-point average (Polich & Martin, 1992). In a sample of HIV positive drug users, P300 latency was negatively correlated with intelligence (Egan, Chiswick, Brettle, & Goodwin, 1993). There are consistent findings of negative correlations between P300 latency and intelligence using the oddball task. None of these studies report significant correlation between P300 amplitude and intelligence.

In addition to the oddball task, the P300 component has been observed in a wide variety of tasks. Two studies in particular have investigated the relation between P300 measures and intelligence in relatively simple cognitive tasks. One study recorded ERPs during the performance of an auditory Sternberg memory scanning task (Pelosi et al., (1992a; 1992b). A significant negative correlation was observed between the amplitude of a positive peak in the latency range of P300 and intelligence. They identified several late peaks in the ERP based on what may be a restrictive latency range. It was observed that the latest peak was visible mainly in the most difficult condition. This may reflect the latency shift of the P300 in this condition rather than the appearance of a different ERP component. The restriction of latency ranges used in the identification of peaks may have obscured the relation between P300 latency and intelligence. Similarly, the amplitude values may not adequately reflect the P300 component. Since these results are based on only 19 subjects and there is difficulty in interpreting the results in terms of P300, these effects must be confirmed in future work.

A comprehensive study of the relation between P300 during cognitive tasks and

intelligence was conducted by McGarry-Roberts et al. (1992). One of the goals of this study was to evaluate the relative merits of reaction time and P300 latency as measures of the speed of processing and its relation to psychometric *g*. They recorded ERPs during the performance of six tasks that have been used in reaction time studies of intelligence. These included a) simple reaction time, b) choice reaction time, c) a physical similarity task using word stimuli, d) a category matching task, e) a Sternberg memory scanning task, and f) a synonym-antonym detection task. P300 amplitude and latency from simple and choice reaction time tasks were unrelated to cognitive ability. The other tasks were more complex and required the presentation of two separate stimuli in each trial. The first stimulus required only the extraction of information while an overt response was required after the presentation of the second stimulus. Significant correlations between full-scale intelligence and P300 latency to the second stimulus were observed in the category matching and Sternberg tasks. P300 amplitude to the second stimulus was correlated $-.37$ with full-scale intelligence in the Synonym-antonym task. Correlations of P300 amplitude and latency to the first stimulus with intelligence were not reported. However, differences between high and low ability groups approached significance for P300 amplitude. This was due to the larger amplitude in the high IQ group. There were no differences between high and low ability groups for P300 latency to the first stimulus. The larger P300 amplitude to the first stimulus for the high IQ group was interpreted as reflecting a greater amount of information extracted from the stimulus. The large P300 amplitude for the low ability group to the second stimulus was attributed to the greater demand for processing resources for the low ability group than the high ability group.

The findings from McGarry-Roberts et al. (1992) are important for several reasons. a)

This was the first extensive investigation using ERPs to cognitive tasks rather than simple oddball tasks. b) There were greater relations between P300 measures and intelligence in the more difficult tasks. This seems to indicate that P300 measures may be sensitive to the level of difficulty. c) The experimental design allows for the analysis of P300 responses in situations that do not require overt responses (unlike reaction time studies). d) The finding that the higher IQ group has faster P300 latency to the second stimulus is consistent with a speed of processing element in intelligence. However, these results are based on a sample of 30 subjects and the level of correlations are small.

Summary

The original goal of ERP investigations of individual differences in cognitive ability was to find a relation between sensory information processing and intelligence. Early reports of large significant correlations between peak latency and intelligence using methods described by Ertl suggested that the speed of processing was related to intelligence. However, the strength of the relation between Ertl's measures and intelligence were weaker than early results suggested. In addition, the criticisms of the measurement procedure and the lack of evidence for the validity and functional significance of the measures makes interpretation of this work problematic. In comparison, EP investigations that have used more conventional measures have failed to demonstrate a relation between peak latency and intelligence. However, there is some indication that EP amplitude measures are positively correlated with intelligence. Schafer (1982; 1984) showed that temporal expectancy and habituation may mediate the relation between EP amplitude and intelligence.

One of the problems of the research to date is that the functional significance of the

measures was not well established. Using the P300 has helped to alleviate this problem. Interpretation of results can call on a vast body of empirical research that demonstrates the conditions under which P300 latency and amplitude vary. In particular, P300 latency has been used as an index of the time to evaluate and classify a stimulus. This makes it useful in the investigation of the relation between speed of processing and intelligence. Preliminary evidence suggests that P300 is negatively correlated with cognitive ability. However, the relation between P300 latency and intelligence is not always demonstrated. The relation between P300 amplitude and intelligence has not received as much attention. P300 amplitude varies with subjective probability, task complexity, stimulus complexity, and task difficulty. While the relation between P300 latency and intelligence was observed in the oddball task, there was no relation between P300 amplitude and intelligence in this task. The two P300 studies that employed more complex cognitive tasks were successful in displaying significant correlations between P300 amplitude and intelligence.

Rationale

This thesis was undertaken to investigate the relation between neural activity reflected by ERPs and intelligence. Specifically, this thesis examines the relation between psychometric measures of intelligence and ERPs collected during the performance of simple cognitive tasks. Most research utilizing ERPs to investigate intelligence have ignored issues regarding the functional significance of the measures that were employed. As described earlier, Johnson (1988) summarized experimental manipulations that affect P300 amplitude. These include subjective probability, demands for processing resources, and equivocation. In particular, differences in demand for processing resources and equivocation will be applied to

individual differences in cognitive ability. Increases in demands for processing resources result in larger P300 amplitude. In general, it is anticipated that demands for processing resources should be greater for those of lower ability. From this perspective, lower ability subjects should have larger P300 amplitude than higher ability subjects. This would result in a negative correlation between P300 amplitude and intelligence. However, increases in equivocation are associated with decreases in P300 amplitude. If equivocation has an effect on individual differences, it is expected that lower ability subjects would display greater equivocation (and therefore smaller P300 amplitude) than higher ability subjects. These individual differences in equivocation would result in a positive correlation with intelligence. Clearly these effects oppose one another. If these factors mediate the relation between P300 amplitude and intelligence, the direction of significant correlations between P300 amplitude and intelligence would depend on the relative contributions of each of these factors.

An experimental method must be utilized that separates the opposing influences of the hypothesized relations of P300 amplitude and intelligence. Since equivocation is greater in more difficult tasks, individual differences due to equivocation may be more evident when difficulty is greater. In order to assess individual differences in intelligence due to equivocation difficulty should be manipulated within a task. Within task variation in difficulty should produce graded increases in the correlation between P300 amplitude and intelligence.

An additional purpose of this research was to provide independent confirmation of the effects observed in previous work. The three tasks from McGarry-Roberts et al. (1992) that displayed the largest correlations with intelligence were selected. These were the synonym-antonym detection task, category-matching task, and the Sternberg memory scanning task.

The first two tasks were conducted as they were previously. The Sternberg task was expanded to allow for further analysis of P300 amplitude and intelligence at several levels of task difficulty. This was done by presenting several trials at each memory set size and computing averages from each memory set rather than computing an overall grand average across set sizes as was done in the original study.

P300 amplitude to the second stimulus in the Sternberg task (the memory probe) has been shown to vary as a function of set size (Houlihan et al., in press). Specifically, the decrease in P300 amplitude as set size increases has been interpreted in terms of the increased effect of equivocation as set size increases. If individual differences in ERP amplitude due to equivocation are related to intelligence, the correlation between P300 amplitude to the probe stimulus and intelligence should increase as set size increases. That is, as the task becomes more difficult, the effects of equivocation on P300 become greater. The higher IQ subject should show smaller effects of equivocation than lower IQ subjects. Therefore, the higher IQ subject should display larger P300 amplitude than lower IQ subjects.

P300 amplitude to the first stimulus in the Sternberg task (the memory set) also varies with set size (Houlihan et al., in press). The first stimulus presented in the Sternberg task is the memory set. Increases in the number of items in the memory set should lead to an increase in demand for processing resources. The demands for processing resources should be greater for those of lower ability who may be considered less efficient in processing. From this perspective, lower ability subjects should have larger P300 amplitude to the memory set stimulus than higher ability subjects. This would result in a negative correlation

between P300 amplitude and intelligence. Furthermore, if the relation between P300 amplitude and intelligence is mediated by the demand for processing resources, the correlation between P300 amplitude and intelligence should become stronger as the effects of the demands for processing resources on P300 amplitude increase.

Another objective of this thesis was to provide support and confirmation of the findings of faster P300 latency in higher ability subjects. This finding has been observed in the standard "oddball" task and in simple cognitive tasks (McGarry-Roberts et al., 1992). Since the relation between P300 measures and intelligence in previous investigations were weak, it is uncertain whether the effects were not reliably different between groups or that there was insufficient statistical power to detect these differences. This thesis will address this problem by increasing the sample size to provide additional statistical power.

Method

The aim of this chapter is to describe the methods and procedures used to collect data. It includes a description of the sample of subjects. The standardized tests that were employed are briefly described. The procedures for conducting the three cognitive tasks are explained. Following this, the ERP recording procedures are described. At the end of the methods section, there is a description of the waveforms. Following this description, the methods of quantifying the ERPs are also stated.

Subjects

A total of 66 female subjects participated in this study. Subjects were recruited at the University of Ottawa. Most of these subjects were enrolled in either Education or Psychology programs. Complete data are available for 61 of the 66 subjects. Four subjects did not have enough artifact-free correct trials to create stable averages. Data from one subject was excluded due to equipment failure. The remaining 61 subjects ranged in age from 18 to 37 years ($M = 22.7$ yrs).

All subjects had normal or corrected to normal vision. None of the subjects reported visual, auditory or other medical difficulties. Informed consent was obtained from each subject before participation in any portion of the study (Appendix A).

Female subjects were employed because there is evidence indicating that females have larger P300 responses than males (Cahill & Polich, 1992; Ditraglia & Polich, 1991; Polich & Martin, 1992). Selecting only females is one of several methods of controlling for these gender differences.

Procedure

Subjects participated in two sessions. Cognitive ability was assessed in the first session using the Multidimensional Aptitude Battery (MAB) (Jackson, 1984). The MAB is a group administered test modeled after the WAIS-R. It consists of ten sub-tests, five verbal and five performance tests. Subjects were allowed 7 min. to complete each sub-test. The MAB yields separate verbal, performance, and full-scale IQ scores. Means and standard deviations for verbal, performance, and full-scale IQ scores are summarized in Table 1. As anticipated with a sample of university students, means IQ scores are above the population normative values. The standard deviations are also lower than the population norms.

Subjects also completed the Eysenck Personality Questionnaire (EPQ; H.J. Eysenck & S.B. Eysenck, 1975). The EPQ yields measures of Extraversion (E) (sociability), Neuroticism (N) (anxiousness, worry) and Psychoticism (P) (tough-mindedness) and Lie (L) (social desirability). Means and standard deviations for the personality variables are presented in Table 2. Correlations among personality and cognitive ability scores are found in Table 3. E, N, and P are normally uncorrelated. However, in this sample, N is negatively correlated with E and positively correlated with P. As has been reported in several other studies, P and L are negatively correlated.

The ERP recording session was conducted within two weeks of the aptitude testing. ERPs were collected during the performance of three types of cognitive task. These are described below.

Stimulus Presentation. A detailed schematic representation of the timing of the stimulus presentation sequence is included as Appendix E. In all tasks, stimulus presentation

was controlled by an IBM compatible computer and presented on a video monitor 0.5 m in front of the subject. Stimuli appeared in black letters on an amber background. All stimuli were centred on the video monitor in the middle of a rectangle. Each trial began with the presentation of a warning signal (***)). It appeared for 50 ms and signalled the start of the stimulus presentation trial. The first stimulus was presented for a duration of 200 ms and appeared 1000 ms after the onset of the warning stimulus. The second (or target) stimulus was displayed 900 ms after the onset of the first stimulus. The target stimulus stayed on the screen for 1600 ms. There were 1.5 seconds between the end of the trial and the onset of the warning stimulus for the next trial. A constant inter-trial interval of 5 seconds was used in all tasks.

Sternberg Memory Task. The Sternberg memory scanning task assesses short-term memory (Sternberg, S., 1966). The first stimulus consisted of a set of one, three, or five letters. Only consonants were used to avoid the construction of words and pseudo words. Subjects were instructed to remember these letters. Therefore, this stimulus is called the memory set. The target stimulus was a single letter. Subjects were instructed to press one button of a mouse when the target letter matched a letter from the memory set. Another mouse button was to be pressed when the target did not match one of the letters in the memory set. The target matched a letter in the memory set on half of the trials. The presentation of the memory set in this version of the Sternberg task differs slightly from the original task. The normal method of presenting the stimuli in the Sternberg task is to present the items in the memory set sequentially with sufficient time to memorize each letter. In this version of the task, all items in the memory set were presented simultaneously and for a

relatively brief (200) ms duration.

The order of presentation was randomized with respect to memory set size and match and mismatch trials. The same random sequence was presented to each subject. There was a total of 480 trials. There were an equal number of trials for each set size. The total 480 trials were broken down into two blocks of 240 trials. A short rest was given after 120 trials (10 minutes) in each block. The exact presentation sequence is included in Appendix B.

Category Matching Task. This task is taken directly from McGarry-Roberts et al. (1992). The first stimulus named one of five categories. These categories were clothing, furniture, sports, animals, and fruit. The target stimulus was always an exemplar of one of the five categories. In half of the trials, the exemplar matched the category and in the other half, the exemplar was a member of one of the other categories. A "yes" response was required when the exemplar and the category matched. The presentation sequence and words used are in Appendix C.

Synonym-Antonym Task. This task is also taken from McGarry-Roberts et al. (1992). Word pairs were presented sequentially (as previously described) in each trial. In half of the trials, the first stimulus and target pair were synonyms. In the other half of the trials, the first stimulus and the target stimulus were antonyms. A "yes" response was required for synonyms and a "no" response for antonyms. The presentation sequence and words used are in Appendix D.

Presentation Order. Each task was preceded by a series of practice trials. There were 25 practice trials for the Sternberg and 10 practice trials for the synonym\antonym task and the category matching task. Additional practice trials were conducted when requested by the

subject or when several errors were committed. One block of the Sternberg task was presented first, followed by the category matching task, the synonym-antonym task, and concluded with the final block of the Sternberg task.

Response Recording. Responses were recorded on a second IBM compatible computer. The subject responded on a three-button Logitech mouse, model C7-3F-95. Response times were accurate to approximately 1 ms. All responses were executed with the index finger of the subjects' dominant hand. The subject was required to keep the middle button of the mouse (the home button) depressed continually until a decision had been reached. To ensure that subjects complied with the response instructions, a message "<HOME>" appeared slightly above the area to which the stimuli were to be displayed while the home button was depressed. This message was removed 1000 ms prior to the onset of the first stimulus. If the subject removed her finger from the home button prematurely, a message was displayed indicating that the home button was not depressed. If this occurred before the appearance of the target stimulus, behavioral responses were not recorded and the trial was excluded from ERP averaging. A "yes" response was completed by releasing the home button, pressing the left mouse button, and finally returning the index finger to the home button. A "no" response was made in a similar manner by pressing the right mouse button.

Response times were divided into two measures: response initiation time (RT) and movement time (MT). RT was defined as the time from the onset of the target stimulus to the time of release of the home button. MT was defined as the time from the release of the home button to the time when the right or left mouse button was depressed. Only trials with

correct responses occurring within 1600 ms of the onset of the target stimulus were recorded.

EEG Recording

EEG and EOG were recorded using Beckman Ag/AgCl electrodes. EEG was measured at Fz, Cz, and Pz according to the International 10/20 system (Jasper, 1958) and referenced to the left mastoid. The EOG was recorded on one channel from electrodes placed on the supra-orbital and infra-orbital ridges of the left eye. A ground electrode was affixed to the forehead.

EEG and EOG signals were amplified using Nihon Kohden EU/5D polygraph amplifiers. Sweep time began 500 ms prior to the onset of the first stimulus and continued for 2500 ms after stimulus onset. A schematic representation of the timing of events is illustrated in Appendix E. Analog to digital conversion provided 300 time points over the sweep (once every 10 ms). Signal averaging was conducted off line and trials in which either EOG or EEG exceeded ± 100 μ V were rejected from the average. Trials with incorrect responses or responses outside of the sweep time were excluded from the averages.

The grand average waveforms for the first stimulus were characterized by a small negative wave at about 125 ms that was evident at Fz, but was difficult to distinguish in most individual averages. A prominent positive wave peaked at around 225 ms. This wave was maximal at Cz. A later positivity with an average latency of 500 ms was most prominent at Pz and had a smaller amplitude and earlier latency at Fz. Because of this scalp distribution, this wave was identified as the P300 component to the first stimulus. There was a prominent negative deflection that developed between the first stimulus and target stimulus (CNV).

The waveforms to the target stimuli consisted of a positivity around 200 ms that was

observed at Fz, but not at Pz. There was a negative wave that peaked around 300 ms. This appeared larger in the mismatch conditions of each task. This negative wave was evident at frontal electrode sites, but was not always evident at parietal sites. A late positivity followed this wave with an average peak latency around 550 ms. As with the first stimulus this wave was largest at Pz and was smaller and had a shorter latency at Fz. Due to the scalp distribution and its latency, this wave was identified as the P300. The P300 waves were evident across all tasks. However the latency and amplitude of the P300 varied considerably among tasks and subjects.

ERP measures for P300 peak amplitude and latency were obtained from the Pz electrode site only. P300 peak amplitude and latency measures were only taken from the Pz electrode site because the amplitude and latency were difficult to detect in many subjects at Fz and Cz. P300 latency and amplitude were quantified using a manual peak detection procedure in InstEP Systems. Amplitude was quantified relative to a prestimulus baseline. This baseline for the first stimulus was the average amplitude of the 500 ms preceding the first stimulus. The baseline for the second stimulus was the average amplitude in the 100 ms interval immediately preceding the onset of the target stimulus.

P300 amplitude was also quantified using the average amplitude in several latency ranges where the peak amplitude is expected to occur. The average amplitude in the 300-400, 400-500, and 500-600 ms windows after the onset of both the first and second stimulus were computed relative to the baselines previously described. These averages were calculated automatically using InstEP Systems software for all EEG electrode sites. These average amplitudes provide an alternative quantification of the ERP amplitude in the latency range of

P300 that avoids subjectivity in identifying peaks and also provides amplitude measures at all electrode sites.

Results

This chapter presents the statistical analysis and the description of the data. Estimates of the reliability for P300 peak amplitude and latency are described first. Then an overview of the performance accuracy for each of the cognitive tasks are reported. The remainder of the results section is organized by ERP task. Analyses of measures derived from the Sternberg task are presented first, followed by the Category Matching (CM) task, and then the Synonym-Antonym (SA) task. Within each of these sections results are organized by dependent variables. Performance variables (RT, MT and RTsd) are reported first. RT means and medians were highly correlated ($r = .98$ to $.99$). Therefore, only the RT means will be discussed to avoid redundancy. Similarly MT means and medians were also highly correlated ($r = .96$ to $.98$) and therefore, only the means for MT will be discussed. The analyses of the ERP variables (P300 peak amplitude and latency and P300 average amplitude) are described next. The results section will conclude with a report of the correlations of measures from the ERP tasks with verbal, performance, and full-scale IQ.

IQ groups were determined by using a median split (Table 4). The lower IQ (LIQ) group contained all subjects with full-scale IQ score (assessed by the Multidimensional Aptitude Battery, MAB) less than 115. The LIQ group had a mean full-scale IQ of 106.2. The higher IQ (HIQ) group was defined by scores greater than 114 on a full-scale IQ of the MAB and had a mean of 122.7.

Performance, ERP, and accuracy variables were analyzed using repeated measures ANOVAs. A summary of the factors and levels in each of the ANOVAs is illustrated in Table 5. Factors in each of these ANOVAs include a between groups factor of IQ group

(levels = Higher; Lower) and a Response Type factor (levels for Sternberg and CM = Match; Mismatch; levels for SA = Synonym; Antonym). In the Sternberg task there was an additional factor of Set Size (levels = one; three; five). For the ERP average amplitude measures, an Electrode site factor (levels = Fz; Cz; Pz) was also included. Significant effects are considered those effects that have a level of significance associated with a Type I error rate of .05. This error rate reflects a Greenhouse-Geisser correction in appropriate instances. Scheffé procedures for post hoc comparison of means were used to follow-up significant effects identified in the ANOVA analyses.

Reliability of P300 Peak Measures

Reliabilities of P300 peak amplitude and latency to the first stimulus were evaluated by examining correlations between P300 measures for "yes" and "no" response categories. Since the first stimulus is equivalent for both the "yes" and "no" response categories, the correlations between these conditions assess stability. Reliability correlations for P300 peak latency range from .67 to .86 and correlations for P300 amplitude range from .70 to .90 (Table 6). The estimates of reliability of P300 peak latency declined slightly as set size increased in the Sternberg task. The correlations for reliability for P300 peak amplitude remained stable across the three set sizes. Reliability for P300 peak amplitude in the CM and SA tasks were lower than those in the Sternberg task.

Accuracy Rate

Accuracy rate was calculated as the percentage of correct responses out of the total of correct and incorrect responses. Trials in which responses were not recorded were excluded from this analysis. Subjects averaged 95% correct across all tasks. An average of 94%

correct was obtained in the Sternberg task (set size one, 99%; set size three 97%; and set size five 86%). SA and CM tasks had 93% and 97% correct respectively. The overall level of difficulty, as indexed by the accuracy rates, indicates that the Sternberg and CM tasks were slightly more difficult than the SA task. The difficulty of the Sternberg task results from the poorer performance on set size five. The accuracy rates are summarized in Table 7.

In the ANOVA for performance accuracy in the Sternberg task, there were no significant differences between IQ groups. There were significant main effects for Response type ($F_{(1,59)} = 13.4, p < .001$) and Set size ($F_{(2,118)} = 289.6, p < .001$). In addition, there was an interaction between Response type and Set size ($F_{(2,118)} = 6.5, p < .01$). The main effect of Response type was due to the better performance on mismatch trials than on match trials. The main effect of Set size was due to the linear decrease in accuracy as set size increased ($F_{(1,59)} = 328.2, p < .05$). The interaction between Set size and Response type was due to the greater accuracy rates to mismatch than match trials in set size three ($F_{(1,59)} = 19.2, p < .05$) and set size five ($F_{(1,59)} = 8.4, p < .05$) but not in set size one ($F_{(1,59)} = 0.1, p > NS$).

The HIQ group performed more accurately than did the LIQ group in the SA task ($F_{(1,59)} = 8.6, p < .01$) but not in the CM task ($F_{(1,59)} = 1.2, NS$). There were no differences in accuracy rate between match and mismatch trials in either the SA or CM tasks.

Sternberg Task: Performance Measures

Reaction time (RT). There were no differences between the IQ groups in mean RT. Responses on match trials were faster than for mismatch trials ($F_{(1,59)} = 214.4, p < .001$). There was a main effect of Set size ($F_{(2,118)} = 227.0, p < .001$) which was due to the linear

increase of RT with set size ($\underline{E}_{(1,59)} = 310.3, p < .05$). There was also a significant interaction between Response type and Set size ($\underline{E}_{(2,118)} = 13.5, p < .01$). The difference between match and mismatch trials was slightly smaller at set size three than at set size one or set size five (Figure 1). The difference between match and mismatch trials was significant at all set sizes. Means and standard deviations for the performance measures (RT, MT and RTsd) for all ERP tasks are summarized in Table 7.

Reaction time standard deviation (RTsd). The HIQ group displayed smaller RTsd than the LIQ group ($\underline{E}_{(1,59)} = 4.1, p < .05$). RTsd was larger for mismatch trials than match trials ($\underline{E}_{(1,59)} = 11.6, p < .001$). There was also a significant interaction of Response type and IQ group ($\underline{E}_{(1,59)} = 7.4, p < .01$). The LIQ group had larger RTsd than the HIQ group to match trials ($\underline{E}_{(1,59)} = 7.9, p < .05$) but not for mismatch trials ($\underline{E}_{(1,59)} = 1.0, NS$). The main effect of Set size ($\underline{E}_{(2,118)} = 38.3, p < .001$) was due to the monotonic increase in RTsd with increases in set size ($\underline{E}_{(1,59)} = 44.4, p < .05$).

Movement time (MT). There were no significant differences in MT between HIQ and LIQ groups. Longer MT was observed for match than mismatch trials ($\underline{E}_{(1,59)} = 35.3, p < .001$). There was a significant effect of Set size ($\underline{E}_{(2,118)} = 29.4, p < .001$). MT increased monotonically with set size ($\underline{E}_{(1,59)} = 36.3, p < .05$).

Sternberg: ERP P300 Peak Measures

P300 peak latency, first stimulus. Means and standard deviations for P300 peak amplitude and latency are summarized in Table 8. The LIQ group had faster P300 latency than the HIQ group ($\underline{E}_{(1,59)} = 4.5, p < .05$). This effect is illustrated in Figure 2. There was also a significant Set size effect ($\underline{E}_{(2,118)} = 53.5, p < .001$) which was due to the linear

increase of P300 latency with set size ($\underline{E}_{(1,59)} = 78.7, p < .05$). This effect is illustrated in Figure 7.

P300 peak amplitude, first stimulus. As seen in Figure 2, P300 amplitude to the first stimulus appears larger for the HIQ group. However, the IQ groups did not differ significantly in P300 peak amplitude to the first stimulus. A main effect of Set size ($\underline{E}_{(2,118)} = 48.3, p < .001$) as displayed in Figure 8, was due to the monotonic increase of P300 amplitude with increases in set size ($\underline{E}_{(1,59)} = 73.3, p < .05$). There were no other significant main effects or interactions.

P300 peak latency, target stimulus. No significant differences were found between HIQ and LIQ groups for P300 latency to the target stimulus (Figure 3 & 4). There was a significant main effect for Response type ($\underline{E}_{(1,59)} = 111.9, p < .001$). As shown in Figure 6, this was due to the faster latency on match than mismatch trials. A main effect was found for Set size ($\underline{E}_{(2,118)} = 290.6, p < .001$). The Set size effect was due to the linear increase of P300 latency with increases in set size ($\underline{E}_{(1,59)} = 406.5, p < .05$) as illustrated in Figure 8.

P300 peak amplitude, target stimulus. There were no main effects or interactions with IQ group for P300 peak amplitude to the target stimulus. Response type ($\underline{E}_{(1,59)} = 4.5, p < .05$) and Set size ($\underline{E}_{(2,118)} = 114.9, p < .001$) main effects were found for P300 peak amplitude to the target stimulus. Larger amplitude was evident for match trials than for mismatch trials (Figure 6). The main effect of Set size, which is clearly evident in Figure 8, was due to the decrease in P300 amplitude as set size increased ($\underline{E}_{(1,59)} = 152.5, p < .05$). There was also a significant interaction of Response type with Set size ($\underline{E}_{(2,118)} = 3.4, p < .05$). Match trials had larger amplitude than mismatch trials at set size one ($\underline{E}_{(1,59)} = 7.1, p$

< .05) but not at set size three ($\underline{F}_{(1,59)} = 0.1$, NS) or set size five ($\underline{F}_{(1,59)} = 5.4$, NS).

Sternberg: ERP Average Amplitude

P300 average amplitude, first stimulus. LIQ subjects had larger amplitude in the 300-400 ($\underline{F}_{(1,59)} = 6.8$, $p < .05$) and 400-500 ($\underline{F}_{(1,59)} = 5.8$, $p < .05$) ms intervals than did HIQ subjects. The significance level for differences between IQ groups was slightly lower in the 500-600 ms interval ($\underline{F}_{(1,59)} = 3.6$, $p = .06$). Amplitudes increased as set size increased in all three intervals (300-400 ($\underline{F}_{(2,118)} = 14.0$, $p < .001$); 400-500 ($\underline{F}_{(2,118)} = 35.0$, $p < .001$); and 500-600 ($\underline{F}_{(2,118)} = 71.6$, $p < .001$)). There were main effects of Electrode site for each of the amplitude intervals (300-400 ($\underline{F}_{(2,118)} = 55.9$, $p < .001$); 400-500 ($\underline{F}_{(2,118)} = 62.1$, $p < .001$); 500-600 ($\underline{F}_{(2,118)} = 75.8$, $p < .001$)). Average amplitude in the 300-400 ms interval at Pz is larger than either Fz ($\underline{F}_{(1,59)} = 49.2$, $p < .05$) or Cz ($\underline{F}_{(1,59)} = 111.6$, $p < .05$) but Fz and Cz do not differ ($\underline{F}_{(1,59)} = 0.2$, NS). The main effects of electrode site in the 400-500 and 500-600 intervals can be explained by the monotonic anterior to posterior increase in amplitude (400-500 ($\underline{F}_{(1,59)} = 69.4$, $p < .05$); 500-600 ($\underline{F}_{(1,59)} = 83.6$, $p < .05$)).

There were also significant interactions of Set size with Electrode site (300-400 ($\underline{F}_{(4,236)} = 5.9$, $p < .001$); 400-500 ($\underline{F}_{(4,236)} = 4.6$, $p < .01$); 500-600 ($\underline{F}_{(4,236)} = 19.3$, $p < .001$)). For the 300-400 ms interval, the Set size effect was significant only at the Fz electrode site ($\underline{F}_{(1,59)} = 21.7$, $p < .05$). In the 400-500 ms and the 400-600 ms interval pairwise comparisons of electrode sites at each set size indicated that Fz and Cz amplitude did not differ at set size one, whereas all other comparisons were significant. Average amplitudes at Pz for each of the time intervals are summarized in Table 9.

P300 average amplitude, target stimulus. There were no significant main effects or

interactions with IQ group for average amplitude to the target stimulus. For the 300-400 ms interval match trials resulted in larger amplitude than mismatch trials ($F_{(1,59)} = 41.9, p < .001$). There were significant differences among set sizes (300-400 ($F_{(2,118)} = 170.1, p < .001$); 400-500 ($F_{(2,118)} = 92.7, p < .001$); 500-600 ($F_{(2,118)} = 44.9, p < .001$)). The Set size effects were due to the linear decrease in amplitude with increases in set size (300-400 ($F_{(1,59)} = 206.0, p < .05$); 400-500 ($F_{(1,59)} = 111.7, p < .05$); 500-600 ($F_{(1,59)} = 58.8, p < .05$)). There were main effects due to Electrode site across all intervals (300-400 ($F_{(2,118)} = 19.4, p < .001$); 400-500 ($F_{(2,118)} = 28.0, p < .001$); 500-600 ($F_{(2,118)} = 26.9, p < .001$)). This electrode effect was due to the linear increase in average amplitude from anterior to posterior sites (300-400 ($F_{(1,59)} = 22.4, p < .05$); 400-500 ($F_{(1,59)} = 32.6, p < .05$); 500-600 ($F_{(1,59)} = 17.4, p < .05$)).

The Set size and Electrode site interaction was significant in all intervals (300-400 ($F_{(4,236)} = 32.6, p < .001$); 400-500 ($F_{(4,236)} = 46.9, p < .001$); 500-600 ($F_{(4,236)} = 60.8, p < .001$)). The effects of set size were stronger at Pz and Cz than at Fz in all three intervals.

There were significant Response type by Set size interactions in each of the intervals (300-400 ($F_{(2,118)} = 33.6, p < .001$); 400-500 ($F_{(2,118)} = 28.6, p < .001$); 500-600 ($F_{(2,118)} = 23.4, p < .001$)). The decrease in amplitude with set size was more pronounced for the mismatch than the match trials.

There were significant Response type by Electrode site interactions for average amplitude in the 300-400 ms interval ($F_{(2,118)} = 52.1, p < .001$) and the 400-500 ms interval ($F_{(2,118)} = 8.5, p < .001$). These interactions are due to the linear increase anterior to posterior for match trials but not mismatch trials.

Category Matching

RT. Mean RT for match trials was faster than for mismatch trials ($F_{(1,59)} = 93.1, p < .001$). There were no other significant effects of Response type or interactions with IQ group for the CM task.

RTsd. The HIQ group had lower RTsd than the LIQ ($F_{(1,59)} = 3.7, p = .06$).

MT. Match trials had longer MT than mismatch trials ($F_{(1,59)} = 7.3, p < .01$).

P300 peak latency, target stimulus. Grand average ERPs to match and mismatch trials for the first and second stimulus are shown in Figures 9 and 10 respectively. Match trials had shorter latency than mismatch trials ($F_{(1,59)} = 33.1, p < .001$).

P300 average amplitude, first stimulus. As shown in Figure 11, LIQ subjects had larger amplitude than HIQ subjects in all three averaging intervals (300-400 ($F_{(1,59)} = 8.6, p < .01$); 400-500 ($F_{(1,59)} = 11.0, p < .01$); 500-600 ($F_{(1,59)} = 4.7, p < .05$)). In all three intervals there were significant main effects of Electrode site (300-400 ($F_{(2,118)} = 33.1, p < .001$); 400-500 ($F_{(2,118)} = 24.0, p < .001$); 500-600 ($F_{(2,118)} = 23.8, p < .001$)). Amplitude was larger at Pz than at either Fz or Cz.

P300 average amplitude, target stimulus. There were no main effects of IQ group for average amplitude to the target stimulus. However, there was a significant interaction of IQ group with electrode site across all three latency intervals. (300-400 ($F_{(2,118)} = 3.6, p < .05$); 400-500 ($F_{(2,118)} = 6.1, p < .01$); 500-600 ($F_{(2,118)} = 4.8, p < .05$)). The LIQ group had greater amplitude than the HIQ group at Fz (300-400 ($F_{(1,59)} = 36.2, p < .05$); 400-500 ($F_{(1,59)} = 36.2, p < .05$); 500-600 ($F_{(1,59)} = 12.6, p < .05$)). The LIQ group also had larger amplitude at Cz in the 300-400 ms interval ($F_{(1,59)} = 24.2, p < .05$) and the 400-500 ($F_{(1,59)}$)

= 8.8, $p < .05$) but not the 500-600 ms ($\underline{E}_{(1,59)} = 0.0$, NS) interval. There were no IQ group differences in amplitude at Pz in the (300-400 ($\underline{E}_{(1,59)} = 4.3 = \text{NS}$) or the 400-500 ($\underline{E}_{(1,59)} = 0.9$, NS). However, the HIQ group had larger amplitude than the LIQ group at Pz 500-600 ($\underline{E}_{(1,59)} = 3.5$, NS)).

Match trials had larger amplitude than mismatch trials in the 300-400 ($\underline{E}_{(1,59)} = 94.5$, $p < .001$) and 400-500 ms intervals ($\underline{E}_{(1,59)} = 35.3$, $p < .001$). There was also a main effect of Electrode site in all intervals (300-400 ($\underline{E}_{(2,118)} = 5.1$, $p < .05$); 400-500 ($\underline{E}_{(2,118)} = 8.3$, $p < .001$); 500-600 ($\underline{E}_{(2,118)} = 37.6$, $p < .001$). The main effect of Electrode site in the 300-400 ms interval is due to the smaller amplitude at Cz than at Fz ($\underline{E}_{(1,59)} = 15.1$, $p < .05$). The main effect of electrode site in the 400-500 ms and 500-600 ms intervals is best described by the linear increase in amplitude from anterior to posterior electrode sites (400-500 ($\underline{E}_{(1,59)} = 8.9$, $p < .05$); 500-600 ($\underline{E}_{(1,59)} = 49.7$, $p < .05$)).

Synonym-Antonym: Performance Measures

RT. There was a significant main effect of Response type ($\underline{E}_{(1,59)} = 11.0$, $p < .01$). This main effect was due to faster RT to match trials than mismatch trials.

RTsd. The HIQ group had smaller RTsd than the LIQ group ($\underline{E}_{(1,59)} = 4.20$, $p < .05$). Match trials were less variable than mismatch trials ($\underline{E}_{(1,59)} = 14.39$, $p < .001$).

Synonym-Antonym: ERP P300 Peak Measures

P300 peak amplitude, target stimulus. P300 peak amplitude to the target stimulus was larger for antonyms than synonyms ($\underline{E}_{(1,59)} = 9.9$, $p < .01$). There were no other significant effects for P300 peak amplitude.

P300 latency. P300 latency to both the first ($\underline{E}_{(1,59)} = 5.4$, $p < .05$) and the target

stimulus ($F_{(1,59)} = 7.3, p < .01$) were faster for the LIQ group than the HIQ group (Figure 14). There were no main effects or interactions with Response type for P300 latency.

Synonym-Antonym: ERP Average Amplitude

P300 average amplitude, first stimulus. The LIQ group had larger amplitude than the HIQ group in all three intervals (300-400 ($F_{(1,59)} = 10.9, p < .01$); 400-500 ($F_{(1,59)} = 10.4, p < .01$); 500-600 ($F_{(1,59)} = 5.6, p < .05$)) (see Figure 13). There were significant Electrode site main effects in all intervals (300-400 ($F_{(2,118)} = 18.8, p < .001$); 400-500 ($F_{(2,118)} = 12.3, p < .001$); 500-600 ($F_{(2,118)} = 26.0, p < .001$)). Average amplitude at Cz was the most negative amplitude across all intervals. The Electrode site main effect is mainly due to the larger amplitude at Pz relative to Cz (300-400 ($F_{(1,59)} = 37.2, p < .05$); 400-500 ($F_{(1,59)} = 35.3, p < .05$); 500-600 ($F_{(1,59)} = 69.1, p < .05$)). There were significant Response type by Electrode site interactions for each interval (300-400 ($F_{(2,118)} = 7.7, p < .001$); 400-500 ($F_{(2,118)} = 11.7, p < .001$); 500-600 ($F_{(2,118)} = 6.8, p < .01$)). Match trials has larger amplitude than mismatch trials only at Fz. However, the difference between match and mismatch trials at Fz was significant only in the 400-500 ms interval ($F_{(1,59)} = 10.4, p < .05$).

P300 average amplitude, target stimulus. There were no significant differences between IQ groups in average amplitude across the three intervals. There were significant Electrode site effects reported for the 400-500 ms ($F_{(2,118)} = 3.9, p < .05$) and 500-600 ms intervals ($F_{(2,118)} = 13.4, p < .001$). These significant effects were due to the linear increase in amplitude from anterior to posterior electrode sites (400-500 ($F_{(1,59)} = 4.8, p < .05$); 500-600 ($F_{(1,59)} = 15.3, p < .05$)).

Pearson Correlations

Pearson correlations were computed between MAB verbal, performance, and full-scale IQ scores and performance measures (RT, RTsd, and MT), P300 peak amplitude and latency and average amplitude measures. Correlations of intelligence with performance measures are summarized in Table 10. P300 peak amplitude and latency correlations are found in Table 11. Correlations of intelligence with average amplitude are in Table 12 for the first stimulus and Table 13 for the second stimulus. In this study, with $n = 61$, correlations of $\pm .21$ reach significance at $p = .05$ as shown in the tables. There is a restriction of range of cognitive ability in this sample. The least amount of restriction of range is for the performance IQ measures. Correlations of $\pm .17$ of any measure with performance IQ would be equivalent to a significant correlation of $\pm .21$ in an unrestricted sample (p. 144, McNemar, 1969). The $\pm .17$ level of correlation is significant at the $p < .10$ level of significance and these are identified in the corresponding tables but are not discussed in the text.

Correlations of IQ with Performance Measures

RT, RTsd, and MT measures from all ERP tasks were correlated negatively with verbal, performance, and full-scale IQ measures. This was evident in all conditions of these tasks.

RT. All IQ scores were negatively correlated with RT. However, none of the correlations with verbal or performance IQ reached significance and only one of the correlations with full-scale intelligence was significant (Sternberg set size 3 "No" response $r = -.21$). The correlations of RT with full-scale intelligence did not vary considerably

between tasks or conditions. The correlations ranged from -.13 to -.21 with an average correlation of -.18.

RTsd. Larger variability is associated with lower MAB scores for all correlations. Three correlations with verbal IQ were significant. One condition in each task had a significant correlation with verbal intelligence. Three of the six conditions in the Sternberg task were negatively correlated with performance IQ (-.33, -.38 and -.26). Six of the ten correlations with full-scale IQ were significant. Full-scale IQ correlations with RTsd ranged from -.06 to -.41 and averaged -.22.

MT. Significant correlations with verbal IQ scores were found for Set Size one of the Sternberg task for both "yes" and "no" responses as well as both conditions of the SA task. Performance IQ scores were correlated with 7 of the 10 conditions. Correlations ranged from -.19 to -.31. The full-scale IQ score correlations reached significance for 8 of 10 conditions with a mean correlation of -.24.

Correlations of IQ with P300 Peak Amplitude and Latency

Most correlations of intelligence with P300 peak amplitude to the first stimulus were negative but were not significant. Most correlations of intelligence with P300 peak amplitude to the second stimulus were positive and only one reached significance (Sternberg task set size 3 "yes" response $r = .21$). Because only one of a possible 60 correlations are significant, these will not be discussed further.

Correlations of P300 latency to the first stimulus ranged from -.07 to .36 with all but two correlations positive. Correlations of performance IQ with P300 latency to the first stimulus were the largest ranging from .12 to .36 with an average correlation of .25. Full

scale IQ correlations were significant in 5 conditions and were slightly lower than correlations with performance IQ measures. Only one of the Sternberg conditions was significantly correlated with verbal IQ. Correlations of intelligence with P300 latency to the second stimulus were also positive. However, only 3 correlations were significant. These three significant correlations of P300 latency to the second stimulus were with performance IQ scores. Overall, P300 latency to both the first and second stimulus is consistently positive. However, only the correlations of performance measures with P300 latency to the first stimulus form a consistent pattern of relations.

Correlations of IQ with ERP Average Amplitude

Correlations with average amplitude to the first stimulus were mostly negative. In general, larger correlations were found with performance scale intelligence than with either verbal or full-scale intelligence. In fact, very few correlations were significant with verbal intelligence. More significant correlations between performance IQ and average amplitude were found at Fz (26 of 30 significant) and Cz (29 of 30 significant) than at Pz (6 of 30 significant). While there were consistent results across intervals, significant correlations were larger in the middle interval (400-500 ms).

There were both positive and negative correlations of intelligence with average amplitude to the target stimulus. Negative correlations were observed between intelligence and average amplitude at the Fz electrode site. The negative correlations were largest in the first interval. As was the case for the correlations of intelligence measures with the amplitude to the first stimulus, the largest correlations were with the performance measures. These correlations were largest in the CM task and also for the mismatch condition of the

Sternberg. A very different pattern of correlations between amplitude and intelligence for the Cz and Pz electrode sites. These correlations tended to be positive. However, the degree of correlation tended to be somewhat lower. The positive correlations were higher with verbal intelligence than either performance or full-scale intelligence. The positive correlations were lower overall, but were highest on the easiest levels of the Sternberg task.

Discussion

This chapter presents an overview and discussion of the major findings. The overview begins with a discussion of response accuracy. This is followed by individual discussion of each dependent variable (RT, RTsd, MT, P300 amplitude, and P300 latency). Later sections will address the relation of psychometric intelligence to speed of processing. Also to be discussed are some possible limitations of the research conducted and some suggestions for future research.

Response Accuracy

While the cognitive tasks used in this study were relatively simple and the accuracy rate quite high, there was some variability in the numbers of errors committed. The Sternberg task, in particular, was designed to assess differences in levels of difficulty. The percentage of correct responses decreased as set size increased suggesting that larger set sizes were more difficult than smaller set sizes. While the overall accuracy rates for the Sternberg and SA tasks were very similar, the accuracy rate was highest in the CM task. Higher ability subjects had slightly greater accuracy rates than lower ability subjects in the SA task but not in either the Sternberg or the CM tasks.

RT

Although RT was negatively correlated with full-scale intelligence on all tasks, only one of the ten correlations was significant at the $p < .05$ level of confidence. Correlations ranged from $-.13$ to $-.21$ and did not vary greatly from task to task. The level of significance for nine of the ten correlations is greater than $p < .10$. These correlations are attenuated due to the restriction of range in intelligence scores. In a larger sample or a sample unrestricted

in range of talent, the level of correlation would reach levels associated with a level of significance of $p < .05$. In general, the size and direction of the correlations are similar to those reported in previous studies (Jensen, 1987; McGarry-Roberts et al., 1992; Miller & Vernon, P.A., 1992). RT is thought to index the time required to process a stimulus including stimulus evaluation, decision, and response preparation, but excluding motor response time (Jensen, 1987; Houlihan et al., in press). Within this context, RT is considered a measure of speed of cognitive processing. Overall, these results are consistent with previous work that relates faster speed of processing on elementary cognitive tasks to higher cognitive ability.

RT increased with increases in task difficulty in the Sternberg task. While the mean RT changed with task difficulty, correlations between RT and intelligence were not affected by the level of difficulty. The CM and SA tasks required access to long-term memory information while the Sternberg task assessed efficiency of short-term memory. The changes in cognitive demands (i.e. level of difficulty task and type of task) did not result in differences in correlations. These results are consistent with previous findings that the common element in the reaction time tasks is what correlates with intelligence rather than something specific to a particular task (Kranzler & Jensen, 1991; McGarry-Roberts et al., 1992; Vernon, P.A., 1983).

MT

MT is defined as the time from response initiation to response completion and is considered a good measure of the speed of motor execution (Jensen & Munro, 1979). MT increased with task difficulty. In particular, MT was longer in larger set sizes in the

Sternberg task. The magnitude of increase in MT with set size was approximately 3 ms per item. This is small in comparison to the change in RT of 28 ms per item. The uncorrected correlations of MT with full-scale intelligence ranged from -.18 to -.31 with an average correlation of -.24 across all tasks. The level of correlation between MT and intelligence is similar to those produced during similar cognitive tasks (McGarry-Roberts et al., 1992) and in the "Hick" paradigm (Jensen, 1987).

Several possible explanations for the relation between MT and intelligence have been offered. 1) The MT-IQ correlations may be artifacts of the apparatus and procedures used to measure MT. This proposal is unlikely due to the findings of significant MT-IQ correlations in studies using different methods and equipment (Buckhalt, Reeve, & Dornier, 1990; Kranzler & Jensen, 1991; McGarry-Roberts et al., 1992). 2) It has also been suggested that MT is affected by individual differences in nerve conduction velocity (NCV) that are also related to intelligence. At this time, there is only one study in support of a relation between NCV and intelligence (Vernon, P.A. & Mori, 1992). The bulk of evidence in this new area of investigation has not demonstrated a significant relation between NCV and IQ (Barrett et al., 1990; Barrett & Eysenck, 1993; Reed & Jensen, 1991; 1992). 3) Another suggestion is that higher IQ subjects are more motivated than lower IQ subjects. Therefore, higher ability subjects perform the motor response faster than lower ability subjects (Buckhalt & Reeve, 1991). This explanation remains plausible, especially considering the finding that MT is also affected by instructions to place emphasis on speed or accuracy of response (Houlihan et al., in press). The speed-accuracy trade-off may represent a strategy adopted by higher ability subjects to complete the task faster than the lower ability subjects.

RTsd

Higher cognitive ability has been frequently associated with lower RT variability on simple tasks (Jensen, 1987). In the present study, full-scale intelligence scores correlated negatively with RTsd. Correlations ranged from $-.06$ to $-.41$ with full-scale intelligence. The average correlation between RTsd and full-scale intelligence was $-.22$. The negative correlations are similar to those reported in previous investigations using RT tasks (Jensen, 1987; McGarry-Roberts et al., 1992). Within the Sternberg task, RTsd increased with increases in set sizes. The correlations of RTsd with intelligence increased with set size for the match trials but not to the mismatch trials. Contrary to this finding, Jensen (1987) found that increases in task difficulty did not lead to larger correlations of RTsd with intelligence in his meta-analysis of the "Hick" paradigm. Both Eysenck (1982) and Jensen (1992) have suggested that the relation between RTsd and intelligence is mediated by variability of information transmission in the nervous system. They suggested that variability in information transmission results in poor quality of information and is thus related to lower ability. Recent investigations of NCV have demonstrated that lower variability in transmission along the median nerve is correlated with higher ability (Barrett et al., 1990; Barrett & Eysenck, 1993). The negative correlations between RTsd and intelligence in this study are consistent with these ideas.

P300 Amplitude: First Stimulus

The first stimulus in the Sternberg task consisted of one, three, or five letters presented simultaneously. Therefore, the size of the display and the perceptual demand for processing increased with set size. P300 amplitude increased along with the increases in set

size. This is consistent with the greater effects of the demand for processing resources than with equivocation (the discrepancy between the amount of information contained in a stimulus and the amount of information actually processed by the subject). While there has been extensive use of the Sternberg task in ERP research, very little research effort has been directed at the encoding or processing of the memory set. In those few reports that have recorded ERPs to the memory set, the presentation of the items in the memory set is serial rather than simultaneous as in the present investigation. In this study, P300 amplitude to the first stimulus increased with set size. This suggests that the variability in P300 amplitude to the first stimulus is due to the increases in demands for processing resources.

In previous work, higher ability subjects tended to exhibit larger P300 amplitude to the first stimulus at Pz (McGarry-Roberts et al., 1992). They speculated that the higher ability group extracted more information from the first stimulus than the lower IQ group. In the present work, this hypothesis was examined by varying the amount of information on each trial (one, three, or five items in the memory set). Contrary to the previous findings, the present study found that P300 amplitude was smaller for the higher ability subjects than for the lower ability subjects in particular at fronto-central electrode placements. The present results suggest that individual differences in information extraction are not associated with individual differences in mental ability. Since P300 amplitude to the first stimulus was associated with increases in the demand for processing resources, the negative correlation between P300 amplitude and intelligence observed in the present study, provides support for the idea that the efficient deployment of processing resources characterizes higher ability individuals.

While the evidence indicates a role of efficient deployment of resources in the P300 amplitude to the first stimulus, there are reasons to be cautious with this interpretation. The negative correlation between mental ability and P300 amplitude to the first stimulus is consistent with this interpretation. However, it may be anticipated that increases in perceptual demand should also lead to relatively larger correlations with intelligence as set size increases. However, increases in set size did not lead to increases in the correlations between P300 amplitude and intelligence.

Hoffman (1990) suggested that the P300 component of the ERP reflects processes of memory storage of information for future use. In this explanation, larger P300 amplitude is associated with greater memory performance. Since enhanced performance should be associated with higher ability, larger P300 amplitude would be expected for the higher IQ group rather than the lower IQ group. This explanation is not consistent with the present study.

It is also possible that the source of the negative correlation between P300 amplitude and intelligence may not be identical to the processes generally referred to in the P300 response. In this study, the P300 wave was difficult to identify at the Fz electrode site in many subjects and this is the site of the largest correlations. In addition, it appears from visual inspection of the waveforms that differences between ability groups begin prior to the P300 wave and continue until the presentation of the second stimulus. This distinction is similar to comments made about differences in ERP amplitude to recognized and unrecognized words (Paller, Kutas & Mayes, 1987). In that study, the difference between recognized and unrecognized words was also more prominent at fronto-central electrode

sites. It is possible, from these observations, that individual differences in ability are related to a frontal negativity rather than P300.

A similar difference between ability groups was evident in ERPs recorded during an auditory Sternberg task (Pelosi et al., 1992a; 1992b). However, the difference between high and low ability was to the target stimuli rather than the first stimulus. The lower ability group displayed more positive ERPs across all electrode sites. However, they did not report findings for the memory set stimulus.

A general negative shift was also reported following a criterion change in a concept learning task (Stuss & Picton, 1978). It was suggested that the negativity may be associated with planning. Greater emphasis on planning would be consistent with higher IQ subjects especially to the first stimulus where a decision is not required. In investigations of memory performance, the relation between performance and P300 amplitude may be affected by the type of strategy employed by subjects. In particular, the relation between P300 amplitude and performance is reduced when elaborative strategies are used (Fabiani, Karis, & Donchin, 1986; Karis, Fabiani, & Donchin, 1984). Since performance is enhanced using elaborative strategies, it may be anticipated that higher IQ individuals would employ such strategies. Furthermore, the employment of strategies may serve to reduce the correlation between P300 amplitude and intelligence. Overall, it is difficult to specify the functional significance of the individual differences in amplitude at the fronto-central electrode sites. However, the overall negative correlation between P300 amplitude and intelligence tends to support the idea that the demand for processing resources is related to individual differences in mental ability.

P300 Amplitude: Second Stimulus

P300 amplitude to the second (target) stimulus decreased as set size increased in the Sternberg task and P300 amplitude was larger to match than mismatch trials in all tasks. This is a stable pattern of results that has been observed in numerous ERP studies using the Sternberg task. Task requirements in these studies have differed in set sizes used, stimulus types (verbal vs spatial), and modality of presentation. Consistent changes in P300 amplitude to the probe stimulus have been reported as a function of set size. Most studies have reported decreases in P300 amplitude to the probe stimulus as set size increases (Brumaghim, Klorman, Strauss, Lewine, & Goldstein, 1987; Gaillard & Lawson, 1984; Gomer, Spicuzza, & O'Donnell, 1976; Pelosi et al., 1992a; Roth et al., 1975). One study did not report amplitude findings (Brookhuis et al., 1981). Others failed to find consistent amplitude changes with set size (Ford et al., 1982; Pratt, Michaelowski, Barrett, & Starr, 1989b). Most studies show larger P300 amplitude to match trials than mismatch trials (Brumaghim et al., 1987; Ford et al., 1982; Gaillard & Lawson, 1984; Gomer et al., 1976; Roth et al., 1975). In the present study, P300 amplitude to the probe stimulus was reduced as set size increased and was larger for match than mismatch trials. These results are consistent with previous ERP studies using the Sternberg task.

Correlations of intelligence with P300 amplitude to the second stimulus tended to be weak but positive in direction. The exception to this was that most correlations of amplitude with intelligence at Fz were negative, especially with performance IQ scores. The negative correlations were larger in the earlier portions of the waveform. The largest correlations with intelligence were evident in the 300-400 ms interval. In this interval, a distinct negative wave

is evident in the mismatch conditions of the Sternberg task and in both conditions of the CM task. The correlations with performance intelligence at Fz in the 300-400 ms interval for these conditions range from -.25 to -.33 and all are significant. The correlations with verbal ability in these same conditions are negligible. Therefore, the negative correlations reflect the greater negativity associated with the an N200 or N400 like component. A previous investigation using these tasks did not report significant differences between ability groups in amplitude to this wave (McGarry-Roberts et al., 1992). However, negative correlations between mental ability and P300 amplitude to the target were reported. The negative correlations between amplitude and intelligence are largely due to the negativity prior to P300 rather than a reflection of the amplitude to the P300 wave. However, the positive correlations between P300 amplitude and verbal intelligence appear stronger at Pz where P300 is largest.

The correlations between intelligence and P300 amplitude to the first stimulus were attributed to individual differences in demand for processing resources. Larger P300 amplitude for the lower ability individual was thought to be a result of greater resources being used by the low ability group. Besides these differences, it was anticipated that individual differences in P300 amplitude to the second stimulus may be influenced more by equivocation than by demands for processing resources. Greater equivocation results in lower P300 amplitude. Therefore, if equivocation is responsible for individual differences in ability, larger P300 amplitude would be expected for the higher intelligence group. If both demands for processing resources and equivocation operate to produce individual differences in P300 amplitude to the second stimulus, they will counteract one another and possibly cancel the

observed effects. This is consistent with the weak positive correlations noted in this study. To fully evaluate the effects of equivocation, individual differences in demands for processing must be eliminated or controlled in some manner. It was also suggested that the correlations with P300 amplitude should be stronger (more positive) in conditions where the effects of equivocation are greatest. This is expected to appear when the set size is largest. However, contrary to these expectations there were no systematic changes in the magnitude of the correlations with changes in set size.

P300 Peak Latency: First Stimulus

P300 latency to the first stimulus increased with increases in set size in the Sternberg task. Contrary to expectations, P300 latency was faster for lower IQ subjects than the higher IQ subjects. Correlations with performance IQ measures were larger than with either verbal or full-scale IQ scores. Uncorrected correlations between performance IQ and P300 latency to the first stimulus ranged from .12 to .36 with an average of .25. Differences in P300 latency between higher and lower ability groups were significant in the Sternberg and SA tasks. Several studies have reported negative correlations between P300 latency and measures of cognitive ability (Howard & Polich, 1985; Ladish & Polich, 1989; Polich et al., 1990; Polich et al., 1986; Polich & Martin, 1992; Egan et al., 1993). Results from these earlier studies were interpreted as an indication that the relation between P300 latency and intelligence was due to differences in speed of processing. However, these studies employed the auditory oddball task to evoke the P300 component. The current study used more difficult cognitive tasks. Furthermore, the first stimulus emphasized encoding of information rather than discrimination or decision processes. One other study using these methods failed to

show any relation between intelligence and P300 latency to the first stimulus (McGarry-Roberts et al., 1992).

P300 latency is thought to index the time required for stimulus evaluation and classification. The increases in P300 latency to the first stimulus with increases in set size are consistent with this proposal. Within this framework it is difficult to account for the longer latency for higher ability subjects. One explanation for the longer P300 latency for the higher ability subjects is that those with lower ability must terminate processing early to prepare for the target stimulus. Therefore, the higher ability group would have more time to devote to processing the first stimulus. This may be interpreted as a strategy employed by higher ability subjects to optimize performance. However, if these strategies are more efficient, differences in the accuracy rates should have been observed. Since accuracy rates were similar in higher and lower ability subjects this explanation remains weak. An alternative explanation for the longer latency for the higher ability subjects is that they devoted more time to stimulus encoding and planning for the target stimulus. Methods of componential analysis revealed longer estimates of encoding time and planning for higher ability subjects in more difficult analogical reasoning tasks (Sternberg, R.J., 1977). Longer P300 latency to the first stimulus is consistent with increases in time devoted to stimulus encoding for the higher ability subjects.

P300 Peak Latency: Second Stimulus

P300 latency to the second stimulus increased as set sizes increased in the Sternberg task. This effect has been illustrated in several studies (Brookhuis et al., 1981; Brumaghim et al., 1987; Ford et al., 1982; Gomer et al., 1976; Pelosi et al., 1992a; Pratt et al., 1989a).

Occasionally this effect has not been observed (Roth et al., 1975; Gaillardé & Lawson, 1984). It appears that increases in P300 latency with set size are consistently found in investigations of the Sternberg memory scanning task. This suggests that P300 may serve as an index of speed of information processing. However, similar to correlations of P300 latency to the first stimulus, the correlations of intelligence with P300 latency to the second stimulus were weak but positive in direction. This is opposite to the anticipated relation between speed of information processing and intelligence. This finding is contrary to several previously reported studies exploring the relation between P300 and ability (Egan et al., 1993; McGarry-Roberts et al., 1992; Polich & Martin, 1992). However, Pelosi et al. (1992b) also failed to find significant correlations between P300 latency and intelligence in the Sternberg task.

Overall, P300 latency was longer for higher IQ subjects. It is difficult to reconcile the differences between this study and previous reports of shorter latency for higher ability subjects. There have been several studies that have failed to demonstrate this effect. Most previous studies that have reported significant correlations between measures of cognitive ability and P300 latency have employed the oddball task. During difficult cognitive tasks, subjects may adopt particular strategies that can mediate the relation between P300 latency and ability measures.

Speed of Processing and Intelligence

It has been proposed that the speed of information transmission is a concept that can explain individual differences in cognitive ability. Jensen (1987) and Vernon, P.A. (1987) have concentrated on the relation between speed of responding in simple cognitive tasks and

intelligence. In general, it has been found that the common element in batteries of reaction time tasks is related to intelligence. This relation between speed and intelligence is found across a variety of simple reaction time tasks that are thought to represent a range of different cognitive processes (Kranzler & Jensen, 1991; McGarry-Roberts et al., 1992). An alternative measure of speed of information processing is provided by EP component latency. This thesis combined these approaches and has used both reaction time measures and EP latency measures to evaluate the relation between speed of information processing and intelligence.

Behavioral measures of processing speed, RT and MT, were negatively correlated with intelligence. The first-order correlations were small and non-significant for RT and slightly larger and significant for MT. However, the distinction between higher and lower IQ groups was not significant for these measures. This may have been due to the low level of correlation between the measures of intelligence and RT and MT. The direction of relation and the level of correlation is very consistent with reports in other investigations using reaction time measures as correlates of intelligence (Jensen, 1987; McGarry-Roberts et al., 1992).

It was also found that the correlation between MT and intelligence was similar to the level of correlation between RT and intelligence. In his meta-analysis of the Hick paradigm, Jensen (1987) also showed that the correlations of RT and MT with intelligence are similar in magnitude. The overall uncorrected correlations from Jensen's (1987) meta-analysis is $-.20$ and $-.19$ for RT and MT respectively. The correlations reported in this investigation are at the same level for RT and slightly higher for MT. Overall, it appears that the stable relation

between intelligence and RT and MT have been reproduced in this experiment.

P300 latency is a reliable index of the time required to analyze and classify a stimulus and is relatively independent of response processes. As an index of the timing of stimulus analysis and classification, P300 latency may serve as a reflection of speed of processing. P300 latency to the probe stimulus reflects some of the same processes indexed by RT. In addition to stimulus evaluation and classification, RT also reflects a response component that is not related to stimulus evaluation time (Houlihan et al., in press). However, there was no significant correlation of P300 latency to the target stimulus with intelligence. This was not a matter of power of the analysis. Correlations between P300 latency and intelligence were positive. The expected relation between intelligence and speed of processing is negative. Higher ability should be related to faster responding but this was not evident in this analysis.

The significantly longer P300 latency for higher ability subjects to the first stimulus does not support a speed of processing relation with ability. This is particularly important considering that P300 latency increased as set size increased in the Sternberg task. This can be used as support that the increase in processing demands leads to increases in stimulus evaluation time. However, it appears that alternative explanations than speed of processing need to be developed to explain the relation between mental ability and P300 latency to the first stimulus.

A similar but weaker pattern of positive correlations between P300 latency and intelligence was also noted for the second stimulus. In addition to the speed of stimulus evaluation, P300 latency to the second stimulus also involves the speed of making simple discriminations or decisions. This would suggest that correlations between P300 latency and

intelligence should be stronger in this condition. For the most part, correlations between P300 latency and intelligence were not significant. In the ERP literature little is known about the relation between processing of the first stimulus and the second stimulus. It is evident in this study that longer P300 latency to the first stimulus is associated with higher ability. It is unknown what type of effect, if any, that the response to the first stimulus has on the response to the second stimulus in these tasks.

The relation between speed of processing and intelligence is revealed in this study by the correlations of RT, and MT with performance and full-scale intelligence. The ERP based index of processing speed, P300 latency, was not faster for higher ability subjects. In fact, higher ability subjects had longer latency than the lower ability subjects. Both RT and P300 latency are thought to index the time required for stimulus evaluation and classification. In addition, RT is also affected by response processes beyond stimulus evaluation and classification. The combination of a positive correlation between P300 latency and intelligence together with the negative correlations of intelligence with RT and MT with intelligence leads to the conclusion that correlations between RT and intelligence and between P300 and intelligence are derived from different sources. The results suggest a role of response processes mediating the relation between RT and intelligence. RT and MT are both affected by response processes and have similar correlations with intelligence. P300 latency is relatively independent of response processes and is not related to ability in this study. However, considering previous reports of faster P300 latency for higher ability subjects the speed of processing explanation of these results still may be favourable.

Structure of Intelligence

The psychometric approach to the description of intelligence has led to a general consensus on a hierarchical structure of abilities. The most general factor of intellectual ability was first described by Spearman (1904) and has subsequently been called *g* or general intelligence. At a less general level of description the distinction of fluid (*Gf*) and crystallized (*Gc*) abilities have received widespread acceptance as important constructs in intelligence. Fluid ability refers to a general reasoning ability while crystallized ability refers to knowledge gained through culture and experience. Intelligence was assessed in this study using the Multidimensional Aptitude Battery (MAB). This test yields separate scores for verbal, performance and full-scale intelligence. Carroll (1993) suggests that full-scale intelligence reflects *g* while verbal and performance scores reflect *Gc* and general visual perception (*Gv*) respectively. (Performance measures have often been interpreted as a reflection of *Gf* rather than *Gv*). This section integrates the findings in this thesis within this structure of intelligence thus providing insight into the relation between ERPs, behavioral measures of processing, and intelligence.

RT, MT, and RTsd were more highly correlated with full-scale than with verbal or performance IQ measures. This is consistent with Jensen's (1992) view that the common factor in reaction time batteries reflects *g*. The measure that is closest to *g* would be the full-scale score.

In general, there were larger correlations of ERP amplitude and latency measures with performance scale IQ and full-scale IQ than verbal IQ. Therefore, it follows that the ERP measures may reflect *g* and either *Gf* or *Gv* but not *Gc*. The exception to this pattern

was the appearance of the positive correlation of P300 amplitude to the target stimulus. The positive correlation was higher for verbal ability than for performance or full-scale ability and may be due to the effects of equivocation on P300 amplitude because it did not appear to the first stimulus. Therefore, the contribution of the process of perceptual demands seems related to general or fluid ability while the process of equivocation is related to crystallized ability.

The effects of restriction of range in the correlations may be responsible for a part of the larger correlation with performance scores. The restriction of range is greater for verbal and full-scale IQ than it is for performance measures. Larger correlations would be expected with performance IQ measures than with the more restricted measures of verbal and full-scale IQ. However, differences in restriction of range are not sufficient to account for the larger correlations with performance and full-scale IQ than with verbal IQ. Since full-scale IQ scores correlate only slightly less than performance measures, this indicates that *g* is important in these measures.

The use of a psychometric test of intelligence as markers of *g*, *Gf*, *Gc*, and *Gv* only provides rough estimates of these variables. In order to identify the relation between ERP measures and particular factors of intelligence, specific test batteries would have to be constructed and a factor analysis conducted with these measures and the ERP measures. The difficulty in this type of undertaking is the problem of sample size. Factor analysis requires many subjects to produce stable results. The collection of ERPs is expensive in resource time per subject and therefore little has been done along this line.

Carroll (1993) included in his survey of human abilities, an analysis of Hendrickson's

1982 investigation that examined ERP measures. Hendrickson's (1982) study involved recording ERPs to simple auditory tones. In this analysis, Hendrickson's string and variance measures along with WAIS subtests were submitted to hierarchical factor analysis. The string measure, which is affected by amplitude (and frequency), loaded on a factor of the performance subtests factor (Carroll identified this as Gv). The variance measure had a primary loading on Gc. Both ERP measures had secondary loadings on a third-order factor that is most probably g. Since the string measure is affected by amplitude, Gv and g may also be related to amplitude measures. However, Widaman et al. (1993) found that ERP peak to peak amplitude to an auditory stimulus negatively correlated with Gc but not Gf. Both of these investigations recorded EPs to simple auditory tones and did not employ cognitive tasks during the EP recording. This correlation was evident for very early peaks of the ERP but not the later endogenous components.

The relation of the string measure to Gv is consistent with the findings in the present investigation. However, this is relying on Carroll's contention that the WAIS and MAB performance tests reflect Gv. The performance tests have been interpreted as referring to Gf. Since Gf and g are more highly correlated than Gv and g in Carroll's model of intelligence, correlations between Gf and g should be larger than correlations between Gv and g. In this study, correlations with performance and full-scale intelligence scores are very similar. This suggests that the performance scores may reflect Gf rather than Gv.

In this study, there is some indication that average amplitude to the target stimulus at Pz is positively correlated with Gc. The correlation with amplitude to the target stimulus at Pz is positive rather than the negative correlation associated with performance measures. The

amplitude at Pz may be a better measure of the variability associated with the P300 complex. While the correlations of intelligence with amplitude to the first stimulus are negative at all electrode sites, the correlations to the target stimulus at Pz are mostly positive. This suggests that the correlation of amplitude due to stimulus evaluation and classification is related to Gc.

ERPs Future?

There are common misconceptions about the nature of ERP research into intelligence. In a commentary on approaches to the study of intelligence, Sternberg, R.J. (1991) states that he "...do[es] not believe that explaining poorly understood IQ scores in terms of an equally poorly understood wave form is significantly going to enhance our understanding of intelligence" (p. 265). The goal of science is to explore some poorly understood phenomena so that it can become comprehensible. In this instance, intelligence is the object of study as it is with Sternberg. It appears that Sternberg may be unfamiliar with the methods and significance of this approach. The explanation of IQ scores by means of ERPs or with any other measure is a valid and desirable area of investigation. ERPs can be used in many different aspects in relation to intelligence. Hendrickson (1982) used ERPs to provide support for an explanatory theory of intelligence. To the extent that ERPs reflect appropriate explanatory constructs for intelligence, these methods can be applied to the study of intelligence.

There are different ways of using ERPs in research. In one strategy, appropriate with early parts of the ERP, measures reflect activation of a defined neural system. This is true of the brainstem evoked potentials for which generators of each peak have been well established. The specificity of these neural sites may be used in intelligence research. For

instance the inter-peak latency of the BAEP should provide a valid measure of the speed of information transmission of simple auditory information. Later endogenous potentials lack this neural specificity. The P300 component, for instance, is generally considered to have multiple generators and these generators have not been adequately identified. However, the use of the P300 in cognitive ability research is justified by referencing P300 measures to the functional significance of the ERP wave. In this sense, ERP measures serve as indicators of the cognitive events that have reliably been shown to elicit the P300 component. When the latency of the P300 is used, it reflects the duration of stimulus evaluation and classification. The present investigation used fairly difficult tasks and found that P300 latency was longer for more intelligent subjects and is consistent with previous reports of longer encoding time in difficult analogical reasoning tasks. If the task is simple, the latency may reflect the speed of making simple discriminations. This relation may be responsible for the reported negative correlation between P300 latency and measures of cognitive ability using the auditory oddball procedure.

It appears from this study that difficult tasks are required to elicit individual differences in P300 related to intelligence. Previous reports with the oddball task did not report significant differences in P300 amplitude. However, P300 amplitude has been significantly correlated with ability during more difficult tasks (McGarry et al., 1992; Pelosi et al., 1992b).

Two specific areas require further work as a follow-up to this investigation. First, the finding of longer P300 latency to the first stimulus was suggested to reflect the additional time for stimulus encoding. This could be tested using analogy tasks or tasks similar to the

ones presented in this study and varying the time between stimuli. The time available for stimulus encoding of the first stimulus has to be systematically varied. Second, it appears that the relation between P300 latency and intelligence within the oddball may be due to the simplicity of the task. Explorations of the extent of this relation would be worthwhile. It has been shown that several factors (i.e. stimulus discriminability, task difficulty, processing demands, etc.) within the oddball task lead to changes in both amplitude and latency. If these factors are systematically varied then the limits of this relation will be known and the relation between intelligence and factors such as speed of processing and task difficulty will be clearer.

ERPs as Measures of Intelligence

An early goal of ERP-intelligence research was to provide a relatively unbiased, culture-free measure of intelligence. Ertl actually developed and marketed such a device. A shortfall of this work was the lack of validation. Measures derived from ERPs (or other biologically based measures) that show modest correlations with intelligence cannot be considered unbiased, culture-free measures of intelligence unless appropriate validation against external criteria also support this contention.

There has been extensive investigation into the predictive nature of scores on intelligence tests. For instance intelligence test scores are probably the best single predictor of academic success. If ERPs are to replace current psychometric intelligence tests, they should display adequate psychometric properties comparable to current intelligence tests. Presently, there is no indication that ERP measures can be used as devices to assess ability. However, the stated purpose of the study by Pelosi et al. (1992a; 1992b) was the

development of an assessment instrument for clinical use. There has been an extensive history in ERP research of substantial correlations between ERP measures and intelligence that have not been consistently replicated. Greater emphasis should be placed on replication of experimental results than on the development of testing instruments.

Summary

The purpose of this investigation was to understand the general cognitive processes that lead to individual differences in psychometric intelligence. Simple cognitive tasks were used to examine individual differences in cognitive processing associated with the changes in the level of difficulty and changes in task demands. ERP recording was concurrent with the performance of these simple cognitive tasks. This allowed a direct comparison of results obtained by traditional reaction time and accuracy measures to results of electrophysiological measures of cognitive behaviour. One motivation for this thesis was to replicate earlier findings of a negative correlation between P300 latency. The current work replicated the experimental effects but failed to find similar relations between ERP measures and individual differences in cognitive ability. However, several important findings were revealed in this study. These results are summarized below.

- 1) A simple one-to-one relationship between P300 amplitude (or P300 latency) and intelligence is not evident. Both positive and negative correlations between P300 amplitude and intelligence were observed. This is not the first time that biological indices have both positive and negative correlations with intelligence. Correlations between glucose utilization and intelligence have sometimes been negative (Haier et al., 1988) and in others positive (Chase et al., 1984; de Leon et al., 1983). Haier et al. (1988) suggested that the relation

between cognitive processing and intelligence depends upon the activity during the uptake period. As was suggested in the work using PET techniques, the relation between ERP measures and intelligence appear to be mediated by the task demands.

2) Contrary to predictions based on a speed of processing explanation of P300 latency, higher ability subjects had longer latency than lower ability subjects. Most previous research has suggested that P300 latency and intelligence are negatively correlated in tasks that require simple classification or discrimination (Egan et al., 1993; McGarry-Roberts et al., 1992; Polich & Martin, 1992). The positive correlation between P300 latency to the first stimulus and intelligence may be associated with longer time devoted to stimulus encoding and planning for future events.

3) Correlations of P300 amplitude with intelligence may depend on the cognitive processes required in the task. Negative correlations were observed when P300 amplitude was affected by differences in the deployment of processing resources. The effect of equivocation is opposite to that of deployment of processing resources and resulted in positive correlations between P300 amplitude and intelligence.

4) Individual differences resulting from the effects of equivocation and perceptual demands were related to different aspects of intelligence. Demands for processing resources were related to fluid abilities. Equivocation was related to crystallized abilities. The correlational evidence for the relation between equivocation and crystallized ability, however, is weak. This provides a source for future investigations.

5) There is a suggestion that the relation between RT and intelligence may be mediated by response processes. This proposition follows from the findings of a negative

correlations between RT and intelligence while P300 latency and intelligence are positively correlated. The processes thought to be reflected in these measures differ only in the inclusion of response related processes that affect RT but have little effect on P300 latency.

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Figures

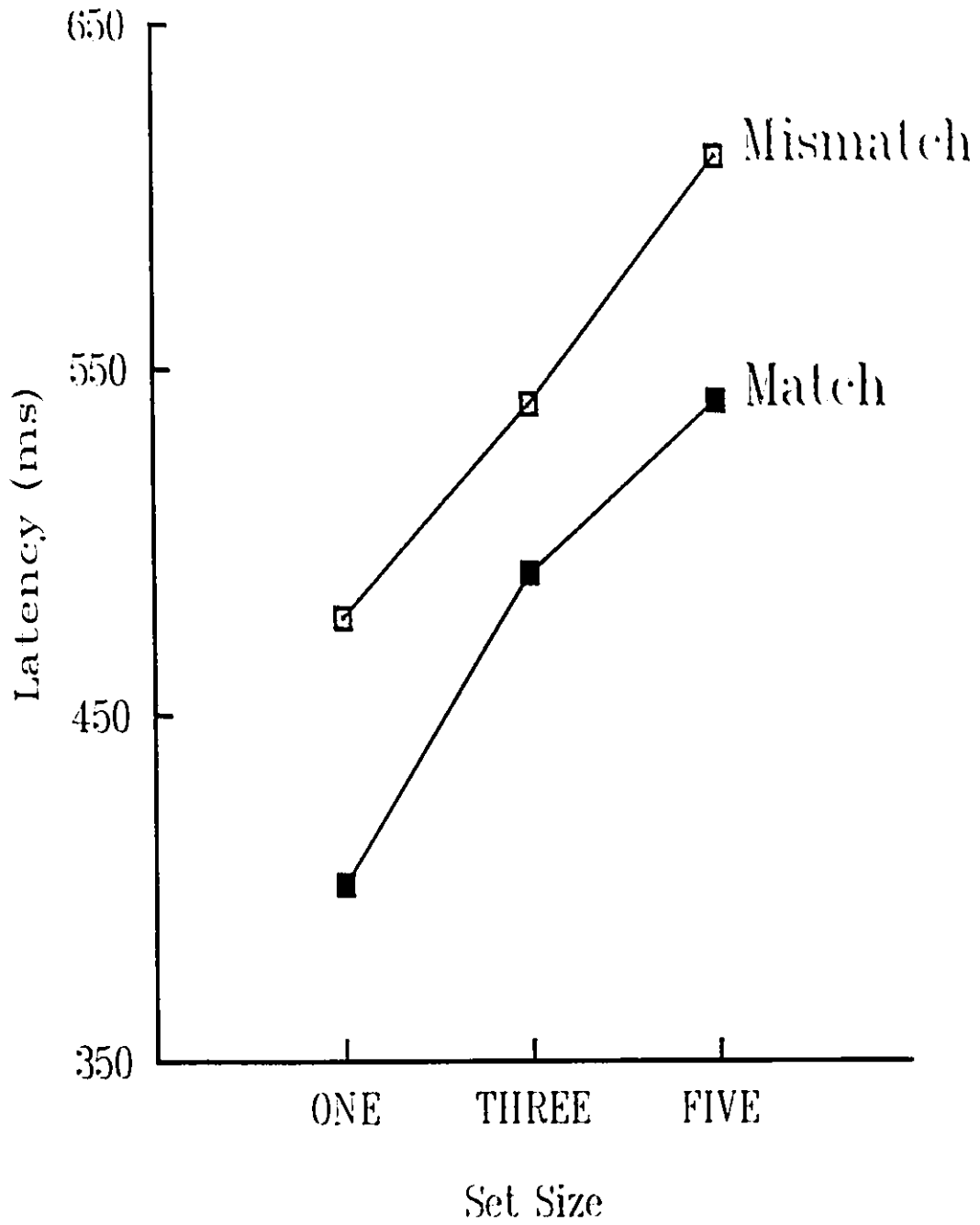
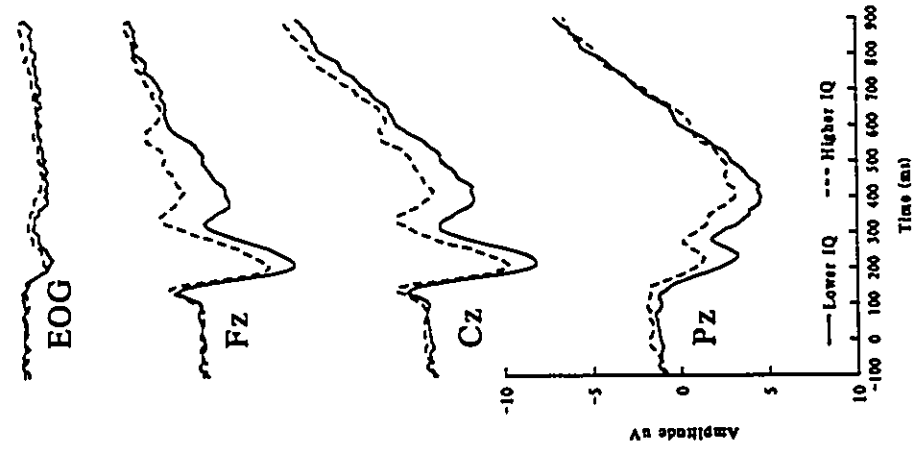
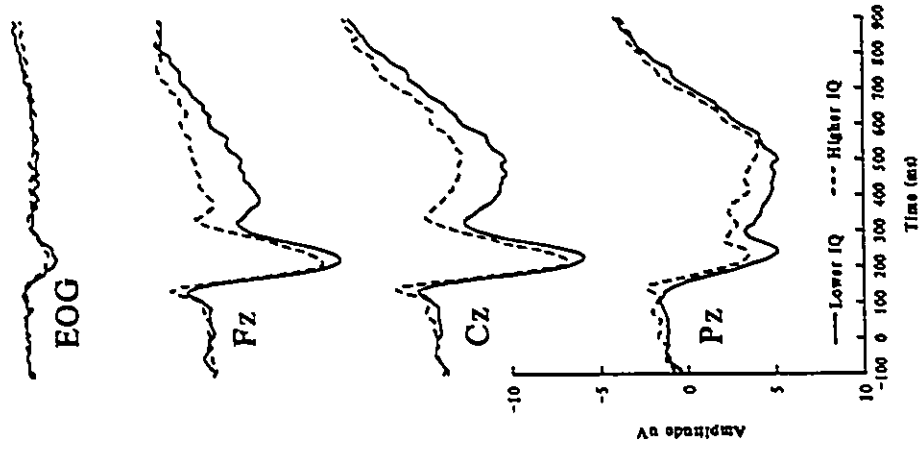


Figure 1
Reaction time means for match and mismatch trials across different set sizes in the Sternberg task.

Set Size 1



Set Size 3



Set Size 5

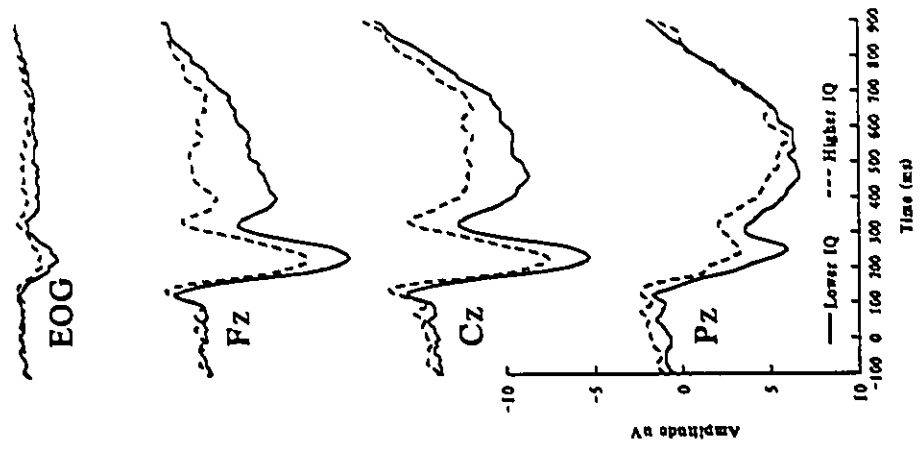


Figure 2
Grand average ERPs for each set size to the first stimulus for Higher and Lower IQ subjects in the Sternberg task.

Set Size 1

Set Size 3

Set Size 5

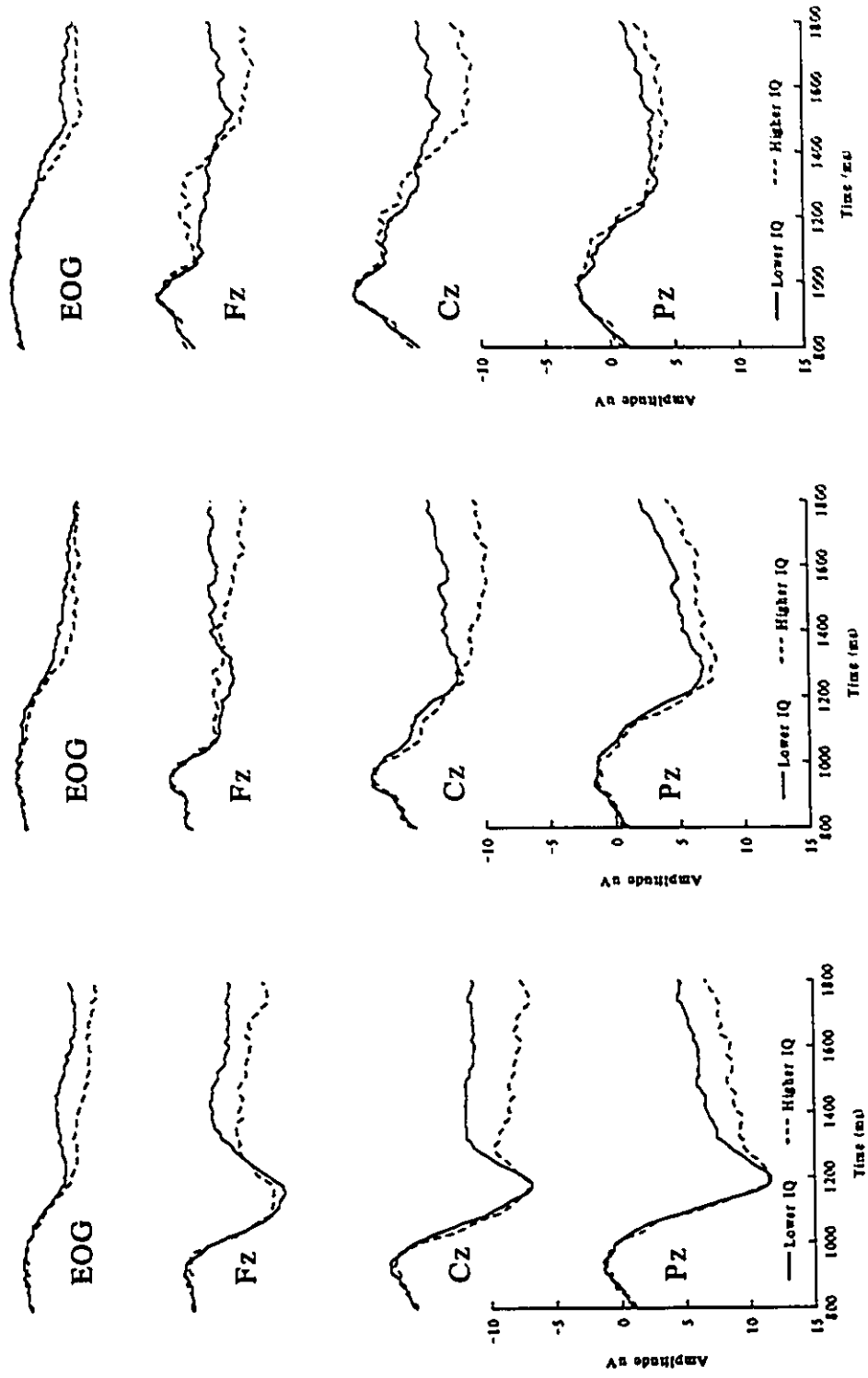
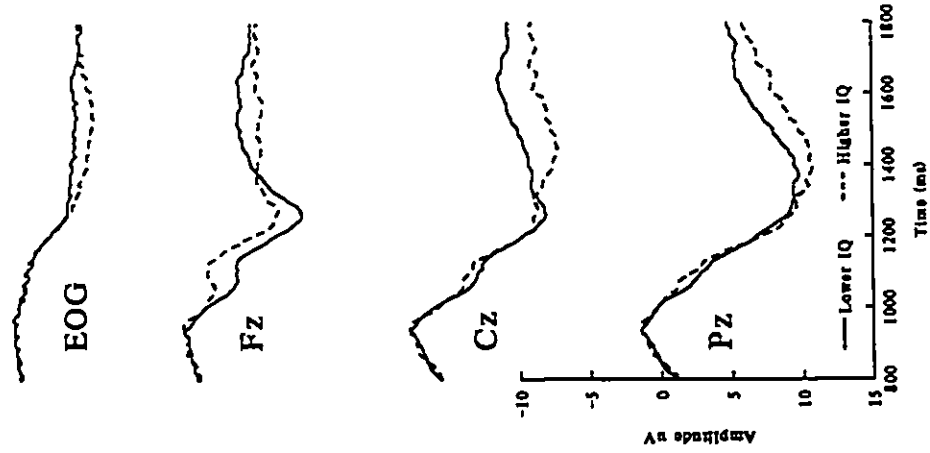
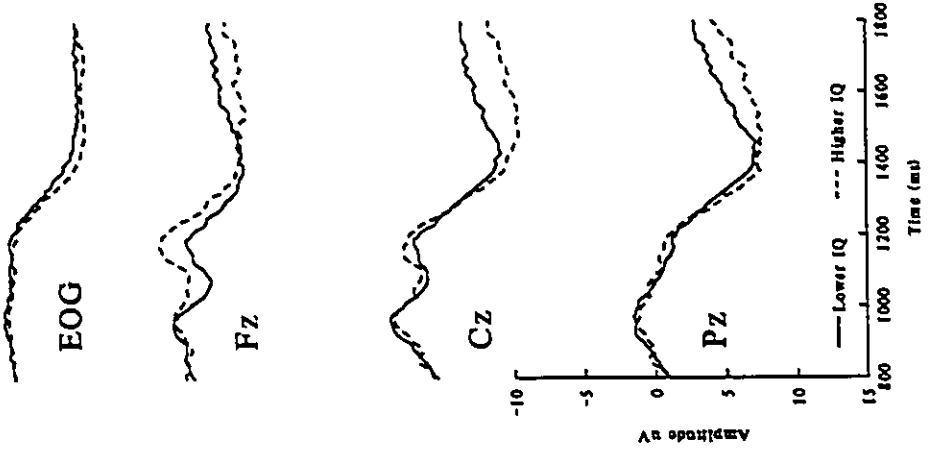


Figure 3
Grand average ERPs for each set size to the second stimulus for Higher and Lower IQ subjects in the Sternberg task for matching trials.

Set Size 1



Set Size 3



Set Size 5

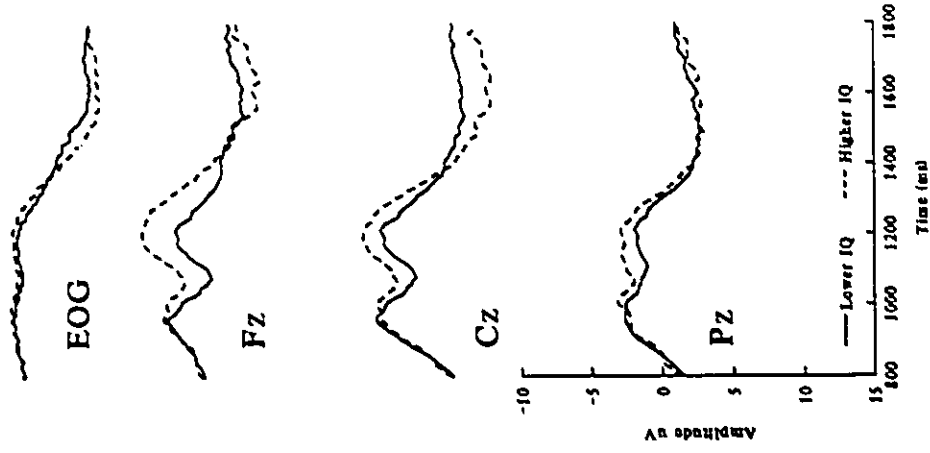


Figure 4
Grand average ERPs for each set size to the second stimulus for Higher and Lower IQ subjects in the Sternberg task for mismatch trials.

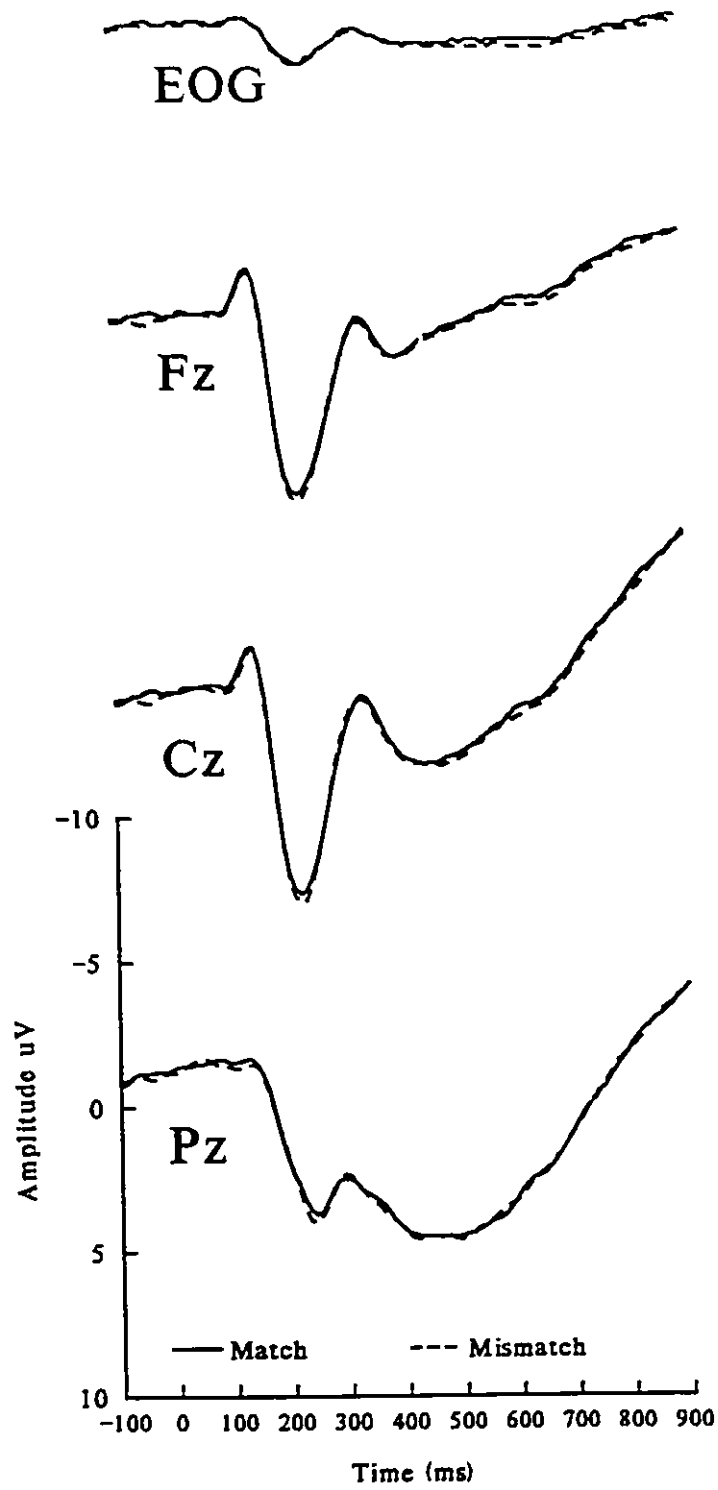


Figure 5
Grand average ERPs to the first stimulus for yes and no responses in the Sternberg task.

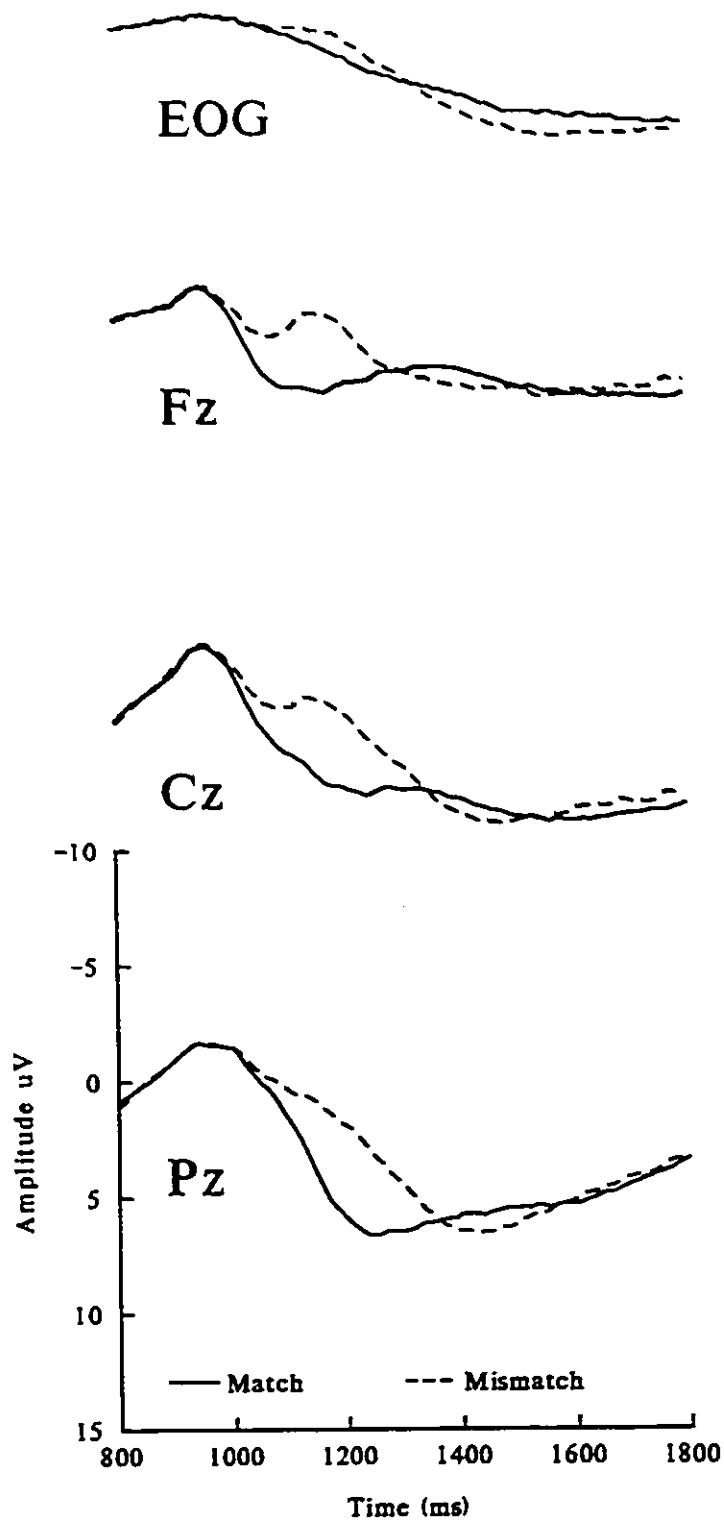


Figure 6
Grand average ERPs to the target stimulus for yes and no responses in the Sternberg task.

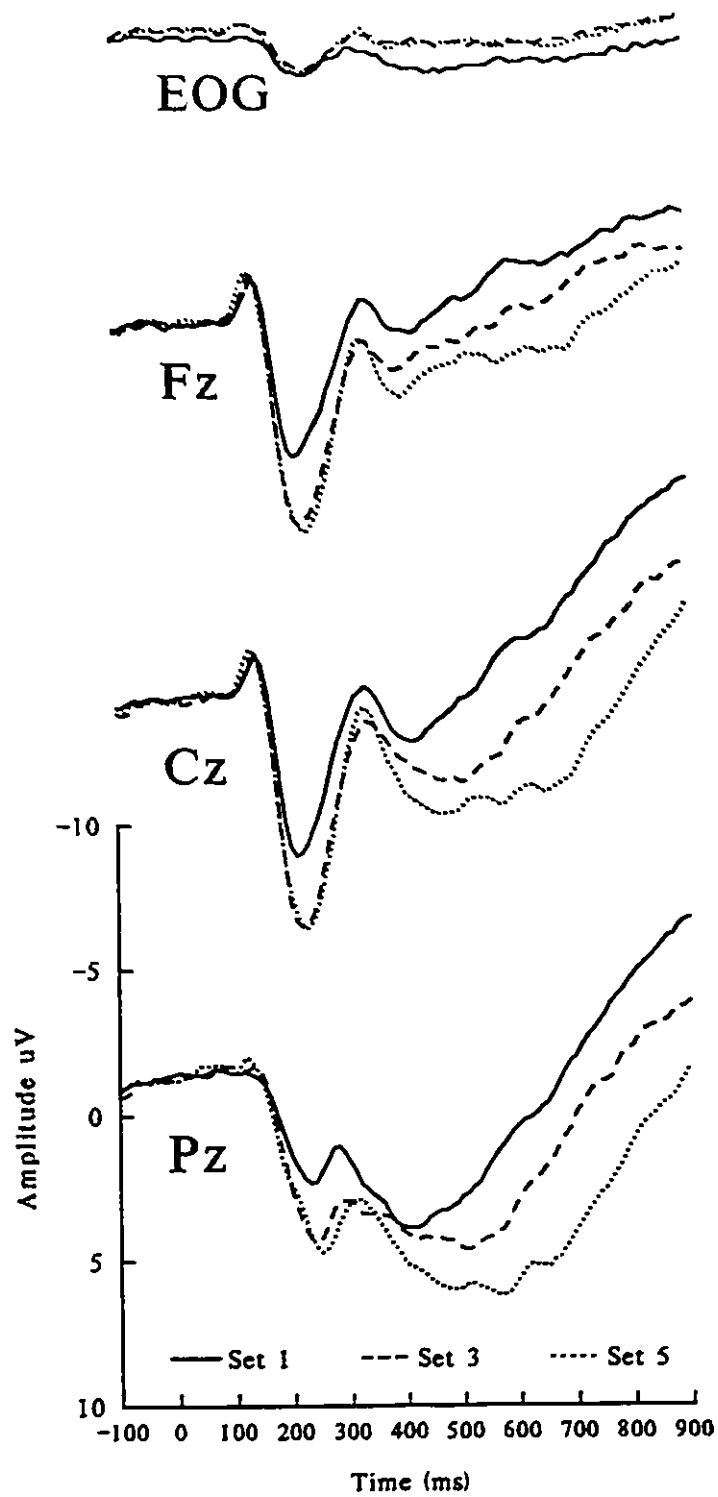


Figure 7
Grand average ERPs to the first stimulus for set size 1, 3, and 5 in the Sternberg task.

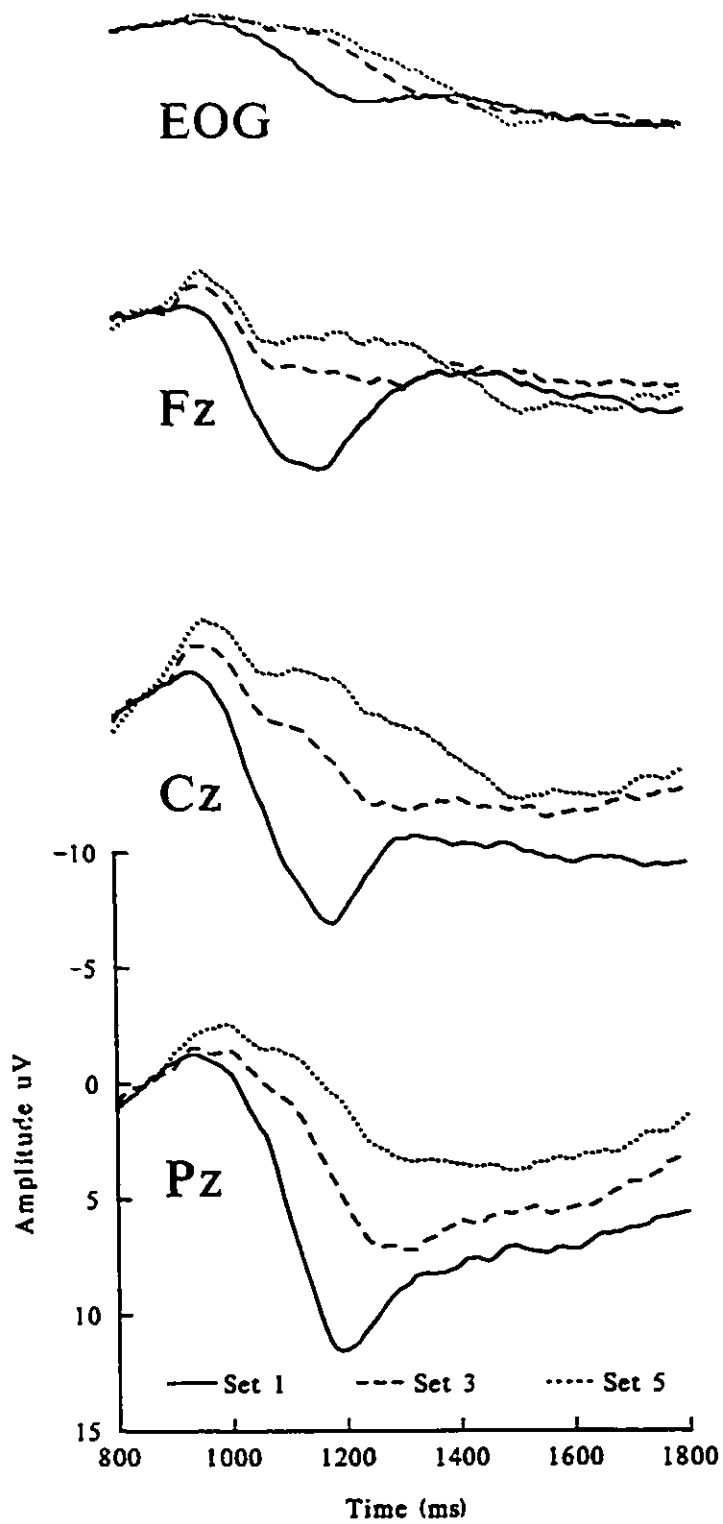


Figure 8
Grand average ERPs to the second stimulus for set sizes 1, 3, and 5 in the Sternberg task.

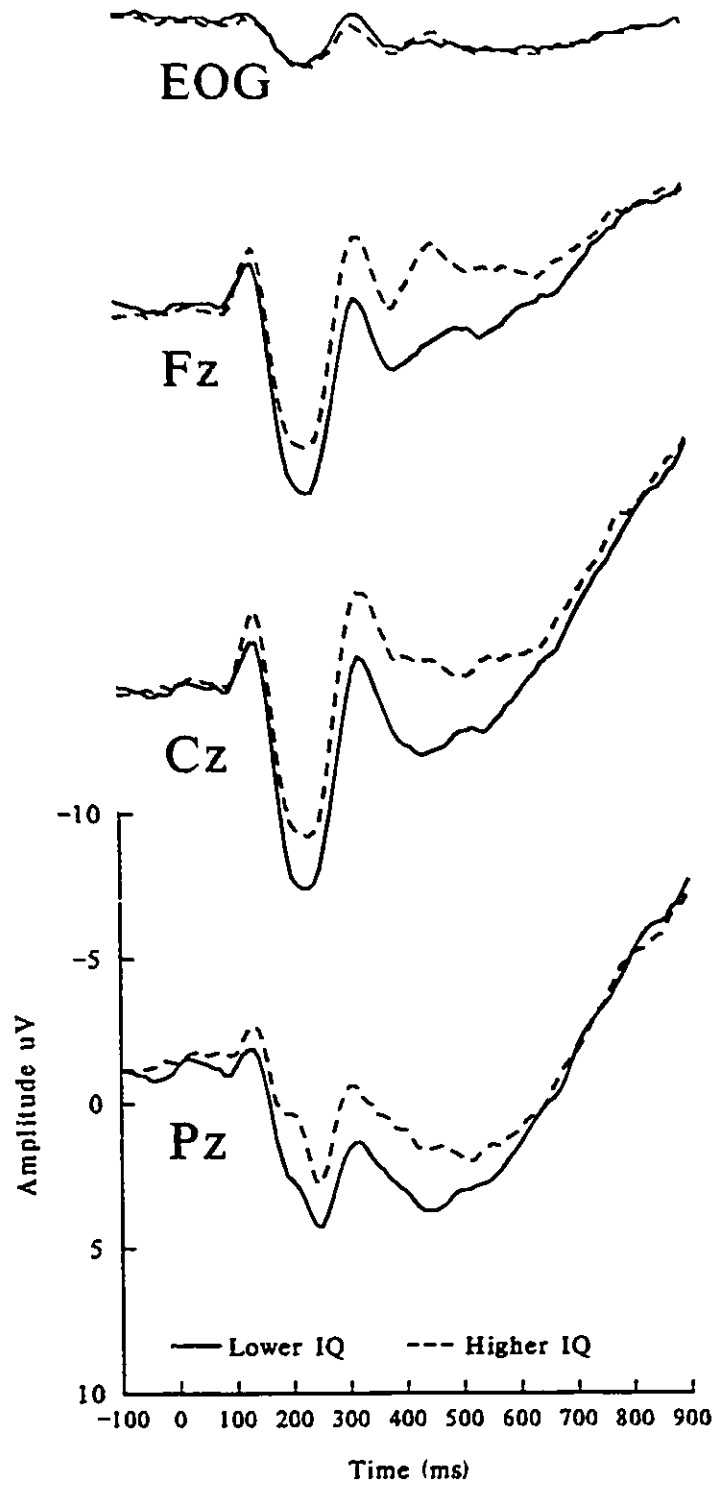


Figure 9
 Grand average ERPs to the first stimulus for Higher and Lower IQ groups in the Category match task.

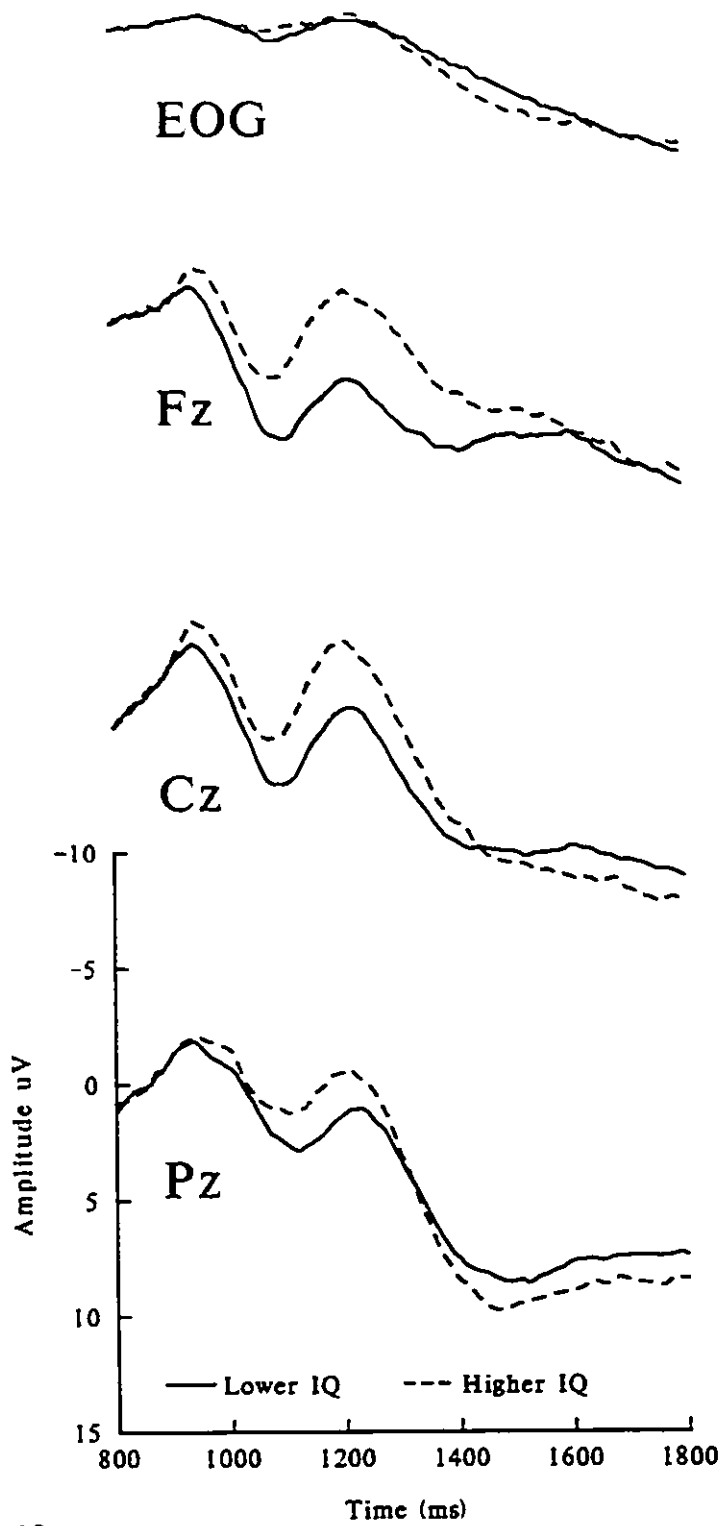


Figure 10
 Grand average ERPs to the second stimulus for Higher and Lower IQ groups in the Category match task.

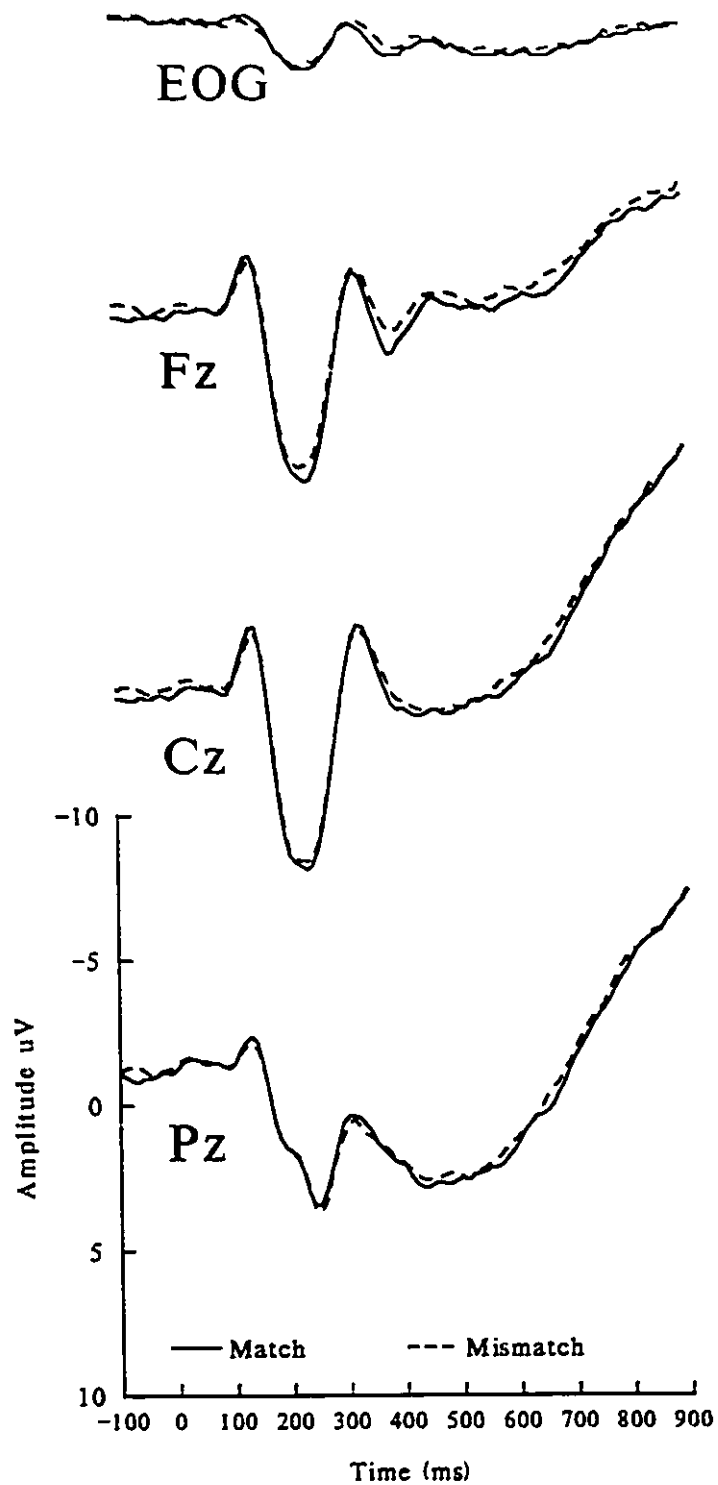


Figure 11
Grand average ERPs to the first stimulus for match and mismatch trials in the Category match task.

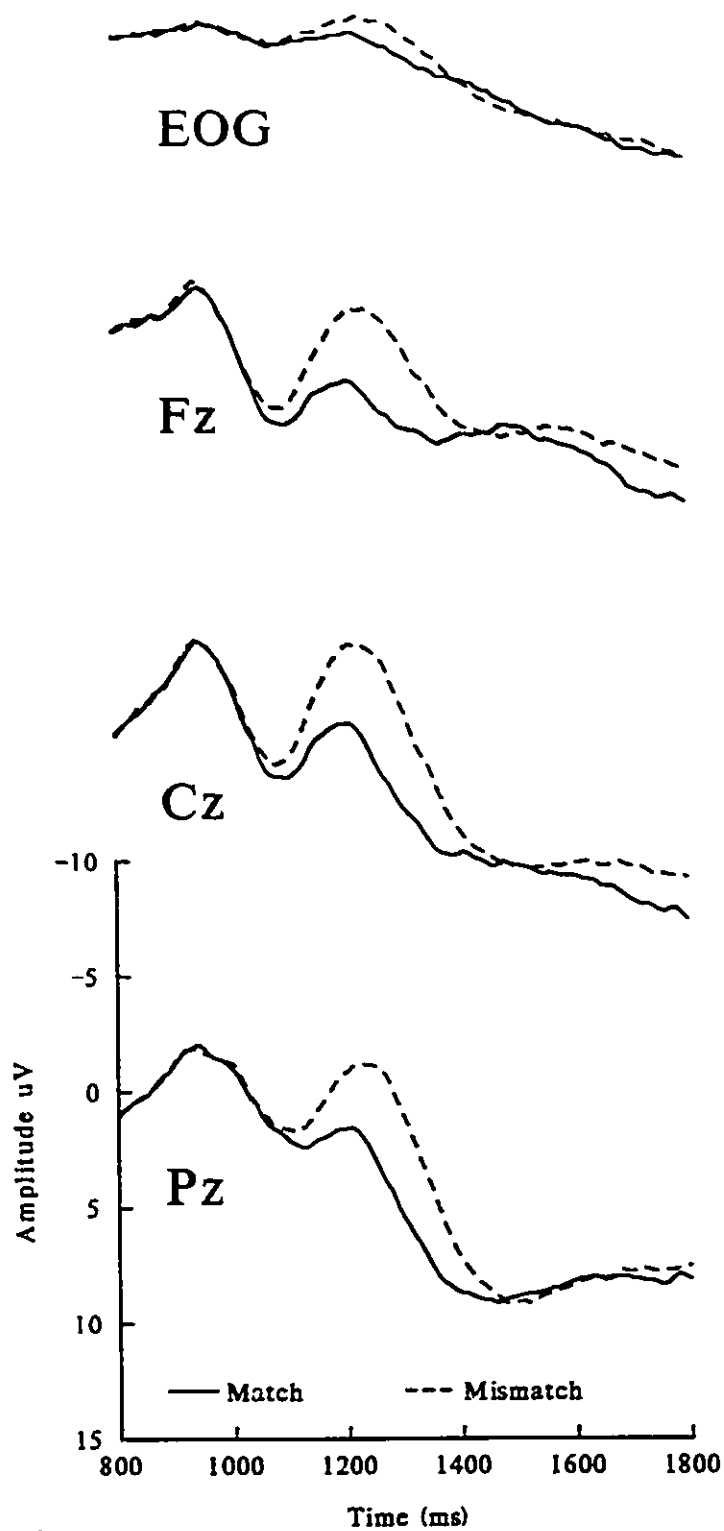


Figure 12
Grand average ERPs to the second stimulus for match and mismatch trials in the Category match task.

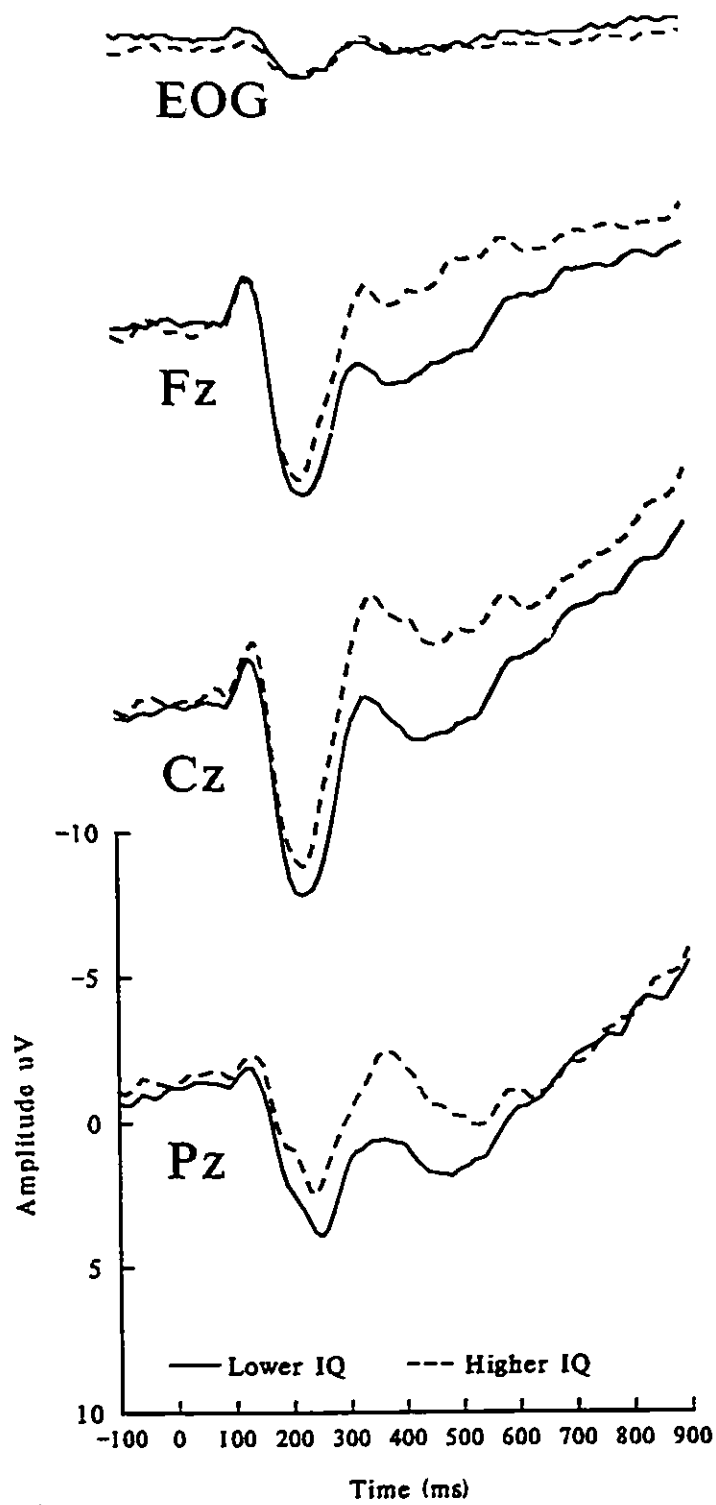


Figure 13
Grand average ERPs to the first stimulus for Higher and Lower IQ groups in the Synonym-Antonym task.

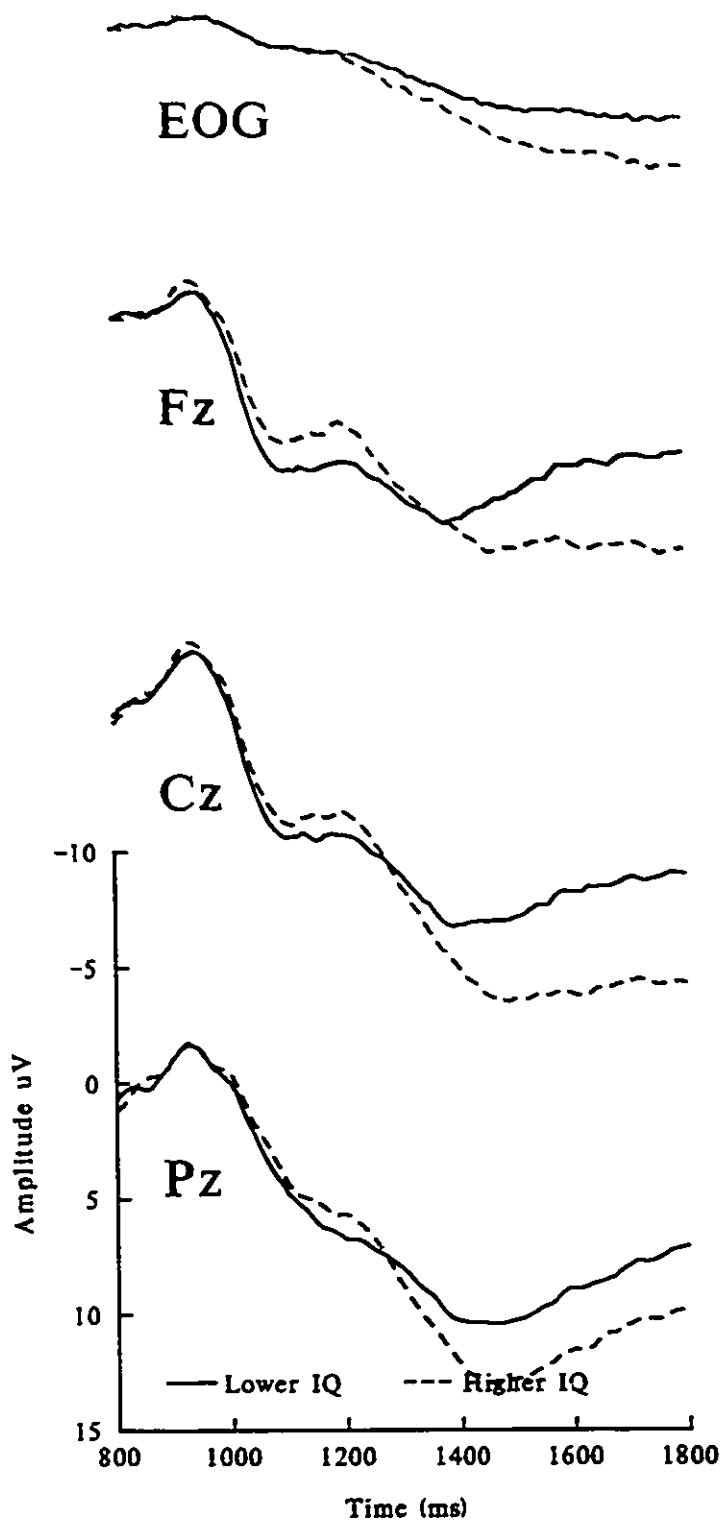


Figure 14
 Grand average ERPs to the second stimulus for Higher and Lower IQ groups in the
 Synonym-Antonym task.

Tables

Table 1

Means and Standard Deviations of Verbal, Performance
and Full-scale IQ

Verbal	Performance	Full-Scale
110.4 (8.4)	116.9 (11.5)	114.0 (9.7)

Table 2

Means of Extraversion, Neuroticism, Psychoticism and Lie Scales from the EPQ

Extraversion	Neuroticism	Psychoticism	Lie
13.5 (4.3)	12.1 (4.9)	2.6 (2.2)	7.3 (3.7)

Table 3

Correlations among Personality and Intelligence Variables

	E	N	P	L	Verb	Perf	Full
Extraversion (E)	1.00						
Neuroticism (N)	-.24*	1.00					
Psychoticism (P)	.01	.24*	1.00				
Lie (L)	-.11	-.17	-.43*	1.00			
Verbal-IQ	-.11	.02	.01	-.01	1.00		
Performance-IQ	-.06	.05	-.02	-.10	.54*	1.00	
Full-scale-IQ	-.04	.06	.00	-.05	.85*	.89*	1.00

*p < .05, n = 61

Table 4
Means and Standard Deviations of Age and Full-scale IQ Scores for
Higher and Lower IQ Groups

	Higher group (greater than 114)	Lower group (less than 115)
n	29	32
age	21.8 (4.0)	23.4 (5.0)
Full-scale IQ	122.7 (5.3)	106.2 (5.0)

Table 5

Factors Used in the ANOVAs for Each Task

Sternberg		Category matching		Synonym-Antonym	
Factor	Levels	Factor	Levels	Factor	Levels
IQ group *	Higher Lower	IQ group *	Higher Lower	IQ group *	Higher Lower
Response Type	Match Mismatch	Response Type	Match Mismatch	Response Type	Synonym Antonym
Set Size	One Three Five				
Electrode site **	Fz Cz Pz	Electrode site **	Fz Cz Pz	Electrode site **	Fz Cz Pz

*This indicates a between subjects factor. All others are repeated measures factors.

**This factor is only applicable to the average amplitude ERP measures in these tasks.

Table 6

Reliability of P300 Peak Amplitude and Latency to the First Stimulus

Task	Latency	Amplitude
Sternberg set size 1	0.81	0.87
Sternberg set size 3	0.74	0.90
Sternberg set size 5	0.67	0.87
Category Match	0.82	0.70
Synonym-Antonym	0.86	0.78

Table 7

Means and Standard Deviations of RT, MT, RTsd, and % Correct in ERP Tasks

Task	Response	Performance Variables			
		RT	RTsd	MT	% Correct
Sternberg Set size 1	Match	400.6 (69.5)	99.4 (30.6)	167.4 (50.0)	99.2 (2.0)
	Mismatch	477.9 (82.0)	118.3 (33.5)	158.1 (43.3)	99.1 (1.3)
Sternberg Set size 3	Match	490.7 (75.0)	117.1 (30.8)	179.7 (56.6)	95.6 (3.8)
	Mismatch	539.7 (90.4)	117.6 (31.3)	159.0 (44.6)	97.7 (2.6)
Sternberg Set size 5	Match	541.2 (97.5)	139.0 (40.7)	187.5 (58.2)	83.8 (8.6)
	Mismatch	612.3 (111.6)	141.6 (34.5)	169.4 (32.9)	87.8 (7.3)
Category Match	Match	609.9 (105.6)	145.8 (32.6)	182.9 (66.2)	97.1 (2.6)
	Mismatch	660.6 (119.6)	150.9 (39.6)	172.9 (65.1)	97.0 (2.6)
Synonym-Antonym	Synonym	615.1 (103.9)	166.9 (41.4)	195.4 (64.6)	93.0 (5.6)
	Antonym	631.0 (104.0)	185.2 (46.0)	193.8 (73.5)	93.2 (6.4)

Table 8

Means and Standard Deviations of P300 Peak Amplitude and Latency

Task	Response	First Stimulus		Second Stimulus	
		Amplitude	Latency	Amplitude	Latency
Sternberg set size 1	Match	5.9 (3.6)	437.8 (89.2)	13.4 (5.2)	305.2 (51.4)
	Mismatch	5.6 (3.9)	434.2 (83.5)	12.1 (4.9)	419.7 (84.0)
Sternberg set size 3	Match	6.8 (3.7)	482.9 (87.0)	9.3 (5.7)	413.1 (90.9)
	Mismatch	6.8 (3.7)	486.6 (85.8)	9.2 (5.0)	521.1 (73.7)
Sternberg set size 5	Match	8.6 (4.2)	531.4 (96.6)	6.1 (5.6)	503.2 (112.8)
	Mismatch	8.6 (4.8)	542.7 (95.9)	5.1 (4.5)	595.2 (110.0)
Category Match	Match	5.3 (3.4)	491.0 (82.3)	10.8 (6.8)	526.5 (77.0)
	Mismatch	4.8 (3.6)	490.6 (83.3)	10.5 (6.9)	576.5 (68.4)
Synonym-Antonym	Synonym	3.2 (3.0)	504.1 (86.2)	12.8 (5.7)	530.2 (63.4)
	Antonym	3.1 (3.7)	508.9 (79.2)	13.6 (6.1)	545.1 (82.5)

Table 9

Means and Standard Deviations of Average Amplitude During Three Intervals at Pz

Task	Response	First Stimulus			Second Stimulus		
		300-400	400-500	500-600	300-400	400-500	500-600
Sternberg set 1	Match	2.9 (3.5)	3.4 (3.6)	1.6 (3.5)	10.1 (5.3)	8.2 (4.2)	7.3 (5.0)
	Mismatch	2.7 (3.8)	3.3 (3.9)	1.2 (3.6)	8.4 (4.6)	9.7 (4.9)	9.4 (4.5)
Sternberg set 3	Match	3.4 (3.7)	4.2 (4.0)	4.0 (3.7)	6.5 (5.1)	6.6 (5.4)	5.8 (5.5)
	Mismatch	3.7 (4.0)	4.4 (4.1)	4.1 (3.6)	2.7 (4.1)	6.0 (4.6)	7.1 (5.1)
Sternberg set 5	Match	3.7 (4.4)	5.6 (5.0)	5.9 (4.5)	2.3 (4.8)	3.2 (5.3)	3.5 (5.7)
	Mismatch	3.9 (4.7)	5.8 (5.3)	6.1 (4.9)	-1.8 (3.9)	0.9 (4.4)	2.4 (4.5)
Category Match	Match	1.2 (3.5)	2.6 (3.5)	2.0 (3.3)	3.0 (5.2)	7.2 (6.3)	8.8 (6.3)
	Mismatch	1.2 (3.3)	2.4 (3.3)	1.9 (3.4)	-0.7 (5.0)	4.1 (5.8)	8.3 (6.5)
Synonym-Antonym	Synonym	-0.5 (3.6)	0.3 (3.5)	0.0 (3.7)	6.6 (4.6)	9.6 (5.3)	11.1 (5.6)
	Antonym	-0.4 (3.5)	0.4 (3.9)	0.2 (3.6)	7.4 (4.7)	10.0 (5.2)	11.7 (6.1)

Table 10
 Correlation of RT, RTsd, and MT with Verbal, Performance and Full-scale IQ Scores

Task		RT			RTsd			MT		
		Verb	Perf	Full	Verb	Perf	Full	Verb	Perf	Full
Sternberg Set 1	Yes	-.09	-.12	-.17*	-.14	-.19*	-.23*	-.23*	-.30*	-.31*
Sternberg Set 3	Yes	-.05	-.17*	-.18*	-.15	-.33*	-.31*	-.20*	-.31*	-.30*
Sternberg Set 5	Yes	-.05	-.17*	-.17*	-.28*	-.38*	-.41*	-.17*	-.30*	-.26*
Sternberg Set 1	No	-.05	-.13	-.16	.02	-.05	-.06	-.22*	-.20*	-.23*
Sternberg Set 3	No	-.11	-.17*	-.21*	-.14	-.26*	-.26*	-.16	-.19*	-.19*
Sternberg Set 5	No	-.12	-.15	-.19*	-.15	-.12	-.18*	-.16	-.24*	-.22*
Category Match	Yes	-.08	-.08	-.13	-.14	-.06	-.14	-.17*	-.23*	-.21*
	No	-.13	-.12	-.18*	-.25*	-.18*	-.28*	-.17*	-.19*	-.18*
Synonym-Antonym	Yes	-.18*	-.07	-.19*	-.25*	-.10	-.23*	-.23*	-.24*	-.23*
	No	-.14	-.08	-.17*	-.11	-.07	-.13	-.29*	-.31*	-.31*

n = 61; * p < .10; * p < .05

Table 11
Correlations of P300 Peak Amplitude and Latency with Verbal, Performance, and Full-scale IQ

Task		First Stimulus						Second Stimulus					
		Amplitude			Latency			Amplitude			Latency		
		Verb	Perf	Full	Verb	Perf	Full	Verb	Perf	Full	Verb	Perf	Full
Sternberg Set 1	Yes	-.08	-.17*	-.14	.04	.12	.11	.04	-.05	-.01	.18*	.01	.09
Sternberg Set 3	Yes	-.07	-.11	-.09	.03	.17*	.12	.21*	.09	.17*	-.05	-.09	-.08
Sternberg Set 5	Yes	.01	-.05	-.02	.12	.28*	.25*	.08	.05	.08	.05	.08	.08
Sternberg Set 1	No	-.04	-.19*	-.14	.24*	.36*	.36*	.06	-.09	-.02	.01	.21*	.11
Sternberg Set 3	No	-.03	-.11	-.07	.02	.18*	.13	.14	.01	.10	-.06	.13	.06
Sternberg Set 5	No	.06	-.01	.05	.11	.30*	.25*	.04	-.03	.03	-.02	.13	.07
Category Match	Yes	-.04	-.19*	-.14	-.00	.26*	.17*	.05	-.04	.00	.18*	.10	.14
	No	-.05	-.10	-.09	-.07	.20*	.10	.13	.07	.12	-.05	.06	.00
Syn-Antonym	Yes	.07	-.01	.03	.13	.31*	.26*	.13	.08	.12	.11	.21*	.19*
	No	-.02	-.07	-.05	.11	.36*	.29*	.14	.06	.11	.10	.24*	.19*

n = 61; * p < .10

Table 12
Correlations of Verbal, Performance, and Full-scale IQ with Average Amplitude to the First Stimulus

	F ₂			C ₂			P ₂		
	Verb	Perf	Full	Verb	Perf	Full	Verb	Perf	Full
300 - 400 ms									
Sternberg Set 1 Match	-.16	-.35*	-.32*	-.23*	.29*	.31*	.15	-.17'	-.18'
Sternberg Set 3 Match	-.03	-.26*	-.19'	-.08	.25*	-.21*	.11	.14	.14
Sternberg Set 5 Match	-.10	-.33*	-.27*	-.10	-.28*	-.23*	.06	.16	.12
Sternberg Set 1 Mismatch	-.16	-.33*	-.29*	-.16	-.29*	-.27*	-.10	-.20'	-.18'
Sternberg Set 3 Mismatch	-.03	-.28*	-.20'	-.08	-.27*	-.21*	.09	.16	.14
Sternberg Set 5 Mismatch	-.06	-.25*	-.20'	-.05	-.18'	-.14	.00	-.06	.04
Category Match Match	.03	-.20'	-.11	-.07	-.27*	-.22*	-.03	-.22*	-.16
Category Match Mismatch	-.01	-.30*	-.22*	-.05	-.29*	-.22*	-.07	-.22*	-.18'
Syn-Antonym Synonym	.00	-.19'	-.14	-.14	-.26*	-.25*	-.21*	-.24*	-.27*
Syn-Antonym Antonym	-.06	-.34*	-.26*	-.18'	-.31*	-.31*	-.26*	-.25*	-.31*
400 - 500 ms									
Sternberg Set 1 Match	-.17'	-.35*	-.32*	-.18'	-.27*	-.27*	-.04	.15	.11
Sternberg Set 3 Match	-.12	-.31*	-.27*	-.17'	-.34*	-.30*	-.10	-.20'	-.16
Sternberg Set 5 Match	-.17'	-.34*	-.31*	-.17'	-.28*	-.26*	-.06	.13	.10
Sternberg Set 1 Mismatch	-.20'	-.37*	-.34*	-.18'	-.33*	-.30*	-.04	-.22*	.15
Sternberg Set 3 Mismatch	-.08	-.32*	-.25*	-.15	-.34*	-.28*	-.08	-.18'	-.14
Sternberg Set 5 Mismatch	-.12	-.29*	-.25*	-.09	-.23*	-.18'	.01	-.06	-.02
Category Match Match	-.08	-.24*	-.20'	-.16	-.26*	-.25*	-.07	-.16	-.14
Category Match Mismatch	-.12	-.36*	-.30*	-.20'	-.32*	-.32*	-.13	-.17'	-.18'
Syn-Antonym Synonym	-.03	-.21*	-.16	-.14	-.26*	-.24*	-.11	-.20'	-.17'
Syn-Antonym Antonym	-.14	-.34*	-.30*	-.24*	-.31*	-.32*	-.21*	-.24*	-.26*
500 - 600 ms									
Sternberg Set 1 Match	-.12	-.24*	-.22*	-.12	-.21*	-.20	.07	.00	.05
Sternberg Set 3 Match	-.09	-.27*	-.22*	-.16	-.35*	-.29*	-.06	-.14	-.10
Sternberg Set 5 Match	-.13	-.29*	-.26*	-.13	-.29*	-.24*	.00	-.09	-.04
Sternberg Set 1 Mismatch	-.13	-.26*	-.24*	-.08	-.23*	-.19'	.11	-.04	.04
Sternberg Set 3 Mismatch	-.10	-.29*	-.24*	-.16	-.34*	-.29*	-.05	-.13	-.09
Sternberg Set 5 Mismatch	-.10	-.25*	-.22*	-.08	-.25*	-.20	.03	-.05	.00
Category Match Match	-.11	-.18'	-.17'	-.14	-.25*	-.23*	-.03	-.11	-.09
Category Match Mismatch	-.13	-.25*	-.23*	-.19'	-.27*	-.27*	-.12	-.09	-.12
Syn-Antonym Synonym	-.10	-.19'	-.18'	-.14	-.25*	-.24*	-.06	-.12	-.09
Syn-Antonym Antonym	-.14	-.26*	-.25*	-.19'	-.25*	-.26*	-.09	-.10	-.11

n = 61; + p < .10; * p < .05

Table 13
Correlations of Verbal, Performance, and Full-scale IQ with Average Amplitude to the Target Stimulus

	Fz			Cz			Pz		
	Verb	Perf	Full	Verb	Perf	Full	Verb	Perf	Full
300 - 400 ms									
Sternberg Set 1 Match	-.03	-.16	-.14	.07	-.06	-.02	.12	-.05	.03
Sternberg Set 3 Match	-.02	-.14	-.11	.13	.04	.09	.15	.03	.12
Sternberg Set 5 Match	-.08	-.11	-.11	-.06	-.02	-.03	-.02	-.07	-.04
Sternberg Set 1 Mismatch	-.12	-.31*	-.25*	.00	-.18*	-.10	.10	-.10	.01
Sternberg Set 3 Mismatch	-.01	-.25*	-.15	.11	-.08	.03	.12	-.05	.06
Sternberg Set 5 Mismatch	-.10	-.30*	-.23*	-.01	-.12	-.07	-.02	-.14	-.09
Category Match Match	-.14	-.31*	-.27*	-.11	-.17*	-.16	-.11	-.12	-.12
Category Match Mismatch	-.08	-.33*	-.26*	-.05	-.19*	-.15	-.06	-.17*	-.13
Syn-Antonym Synonym	.05	-.20*	-.09	.05	-.11	-.03	.04	-.11	-.03
Syn-Antonym Antonym	.05	-.16	-.07	.03	-.09	-.04	-.04	-.15	-.12
400 - 500 ms									
Sternberg Set 1 Match	.05	-.03	-.01	.18*	.06	.12	.23*	.06	.15
Sternberg Set 3 Match	.00	-.08	-.05	.19*	.09	.15	.21*	.06	.17*
Sternberg Set 5 Match	-.04	-.07	-.05	.04	.05	.06	.07	.13	.06
Sternberg Set 1 Mismatch	-.10	-.19*	-.19*	.04	-.14	-.07	.12	-.09	.01
Sternberg Set 3 Mismatch	-.01	-.21*	-.12	.14	-.08	.05	.20*	-.04	.11
Sternberg Set 5 Mismatch	-.05	-.31*	-.20*	.05	-.12	-.03	.06	-.12	-.02
Category Match Match	-.14	-.25*	-.23*	-.04	-.12	-.10	.03	-.03	.01
Category Match Mismatch	-.09	-.23*	-.19*	-.01	-.10	-.07	.09	-.03	.05
Syn-Antonym Synonym	.00	-.15	-.09	.05	-.05	.00	.11	.00	.06
Syn-Antonym Antonym	.00	-.11	-.05	.09	-.01	.05	.10	-.01	.05
500 - 600 ms									
Sternberg Set 1 Match	.03	.10	.09	.15	.14	.17	.18	.12	.17
Sternberg Set 3 Match	.02	-.02	.00	.21*	.10	.18	.19	.07	.15
Sternberg Set 5 Match	.03	.04	.06	.12	.12	.15	.09	.06	.10
Sternberg Set 1 Mismatch	-.09	-.09	-.09	.06	-.05	.02	.09	-.03	.04
Sternberg Set 3 Mismatch	-.06	-.04	-.03	.07	.00	.06	.09	-.03	.06
Sternberg Set 5 Mismatch	-.02	-.02	.01	.08	.07	.11	.05	-.04	.03
Category Match Match	-.11	-.19	-.19	.01	-.08	-.05	.06	-.01	.03
Category Match Mismatch	-.05	-.10	-.09	.07	-.01	.03	.15	.05	.12
Syn-Antonym Synonym	.04	-.01	.02	.12	.04	.10	.16	.07	.13
Syn-Antonym Antonym	.04	.03	.06	.13	.09	.13	.16	.08	.14

n = 61;

p < .10;

* p < .05

Appendices

Appendix A: Research Participant Consent Form

I, _____ consent to take part in a study that will record the electrical activity of the brain that occurs when choosing to respond to stimuli presented on a computer monitor. The aim of the study is to examine cognitive performance and the conditions that may be related to the amount of information extracted from a stimulus. I will be asked to complete the Multidimensional Aptitude Battery, a standard paper and pencil test that will take approximately 90 minutes to complete. In addition, Mike Houlihan the research assistant of Dr. Stelmack, the principle investigator, has explained to me that I will be asked to complete three tasks that will take about two hours to complete. Individual appointments will be scheduled for the remaining tests after I have completed the first testing session. In the first of the three tasks, I will be shown a pair of words on a computer monitor and will respond by pressing the left button on a mouse if the pair are synonyms and the right button if the pair are antonyms. In the second task, I will see a word that describes a category of objects. After a short delay I will see a second word and will respond by pressing the left button if this word is an object in the category described by the first word and I will press the right button if the word is a member of another category. In the third task, I will see up to three letters which I memorize. Later I will see a single letter and I will press the left button if the letter is one previously displayed and if it was not one of the previous letters I will respond by pressing the right button. The electrical activity of the brain is recorded from small electrodes on my scalp while I am performing this task.

Seven small electrodes will be attached to my scalp to record the electrical activity of the brain. If necessary, the skin is rubbed gently with a small wooden applicator to remove oil from the surface of the skin. The electrodes will be attached with a small dab of water-soluble cream and tiny adhesive collars. The cream is easily removed by the research assistant with a moist cotton ball leaving no visible trace of the cream.

There is no danger or risk to health or self-esteem in this study. All procedures have been extensively pretested and they have been used routinely for many years in this and other laboratories. The procedure takes about 2 hours to complete. I understand that I will not be paid to participate in this study and that my participation is entirely voluntary. I also understand that I may withdraw from the study at any time, even after signing this form, without jeopardy or penalty of any kind. Any information about me that is collected during this study will be kept confidential, and when results are published, I will not be identified in any way.

Dr. Stelmack can be reached at 564-9158, or in room 408b Montpetit Hall.

There are two copies of this consent form one of which you may keep.

_____ NAME (print)	_____ SIGNATURE (participant)	_____ DATE
_____ NAME (print)	_____ SIGNATURE (witness)	_____ DATE
I have explained the nature of the study to the participant and believe that she/he has understood it. Mike Houlihan _____	_____ SIGNATURE (researcher)	_____ DATE

Appendix B: Stimuli for Sternberg Memory Task

Memory Set	Probe	Memory Set	Probe	Memory Set	Probe
FVP	F	LNS	N	PLXRS	N
HVD	D	PJXSK	M	NFTIJ	H
H	D	NDF	T	P	N
GWF	W	N	W	BVD	B
T	T	N	V	RXMFB	Z
W	P	SGMTB	M	ZDGVF	T
TBWGP	W	JNK	L	WNS	N
SGN	P	HJV	J	FKCZB	T
LJC	Z	PWLHD	J	P	H
FQT	T	BJFRL	C	R	R
VZWGJ	B	QZVXN	T	FXG	H
PHDJF	H	JGTHM	H	K	K
BGDQR	R	VKG	H	V	V
G	G	F	B	DBG	B
TNG	G	BWVCG	R	V	H
V	T	HBS	W	W	Z
C	C	M	H	MZBCR	M
TXCJP	T	Z	G	WLBTC	Q
NGL	H	JVX	Z	LHD	H
VDCNW	N	H	Q	TDVGF	S
FNV	N	CPD	N	S	C
DXJGL	Z	M	M	J	J
ZLQ	V	PBVND	P	LRD	L
NRBVH	S	C	C	WXRLD	X
JGR	J	B	B	DTJVK	J
NRW	N	XGRVF	X	KBNCD	D
PLQMT	J	TKN	N	DKX	G
F	X	F	X	M	L
XLD	D	XBRVL	V	BVD	F
MBN	P	RHK	K	Z	R
PLGNQ	L	H	H	SWCQR	Z
J	J	J	J	LJNCQ	Q
HND	N	ZBF	Z	V	V
NBDKM	B	B	L	K	K
TJWLQ	Q	MRHTS	T	FXJ	F
LKB	L	QVK	N	T	T
C	R	GLB	F	PCG	P
HCS	N	VWCXQ	Q	GNCRK	R
HQMLS	L	V	N	W	L
RVWGP	V	V	W	T	T
NRJ	X	G	G	PGZ	Q
MBSNL	X	X	K	G	G

Z
N
KFPDS
LQWRT
LXQZF
GFVJP
WPTKG
LCX
NKS
XMT
X
DHILFJ
MRDVL
V
D
FST
C
M
FCZ
RVT
G
NSV
GTV
BDS
XPJ
S
XLN
KGC
X
PCMXH
T
P
DBM
MSJ
K
RQK
J
KDH
QHC
NXX
S
ZJD
ZHT
LQRMD

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G
X
KGW
X
K
RLP
X
JVB
V
N
LJK
HPLWD
R
FKGJW
R
CFTXJ
W
TRXXM
VSTJB
RVL
BSF
RZNPW
CDRHP
S
LRSFN
G
HNP
TVC
XFSJW
XGT
WSHBF
TVGPL
TCSDN
LWFB
V
P
V
S
SNL
FHQNT
ZFBGW
J
RDVMQ
NDX

Q
X
G
J
K
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X
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V
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P
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D

L
JMKWD
HLTFQ
COX
CPTKR
THM
GFWCN
GWCKR
G
FMR
GPT
L
L
V
C
LPNVD
QVMKX
CRX
ZDW
RQWKT
K
GNTWK
HRBLM
HCZXB
SND
BJDRM
BZR
LMV
M
QRF
F
J
WSPRF
GLX
KJZ
WFV
QXWSM
JNZCB
BCGMH
M
ZKX
N
X
GMCVZ

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M
Z
M
X
Q
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X
F
R
D
F
D
Z
H
M
K
D
X
C

GKJ	H	STJ	R	FXH	N
LKTX	K	V	V	HXTFW	X
PFB	P	PTQZV	Q	NNCKS	N
CPWJL	F	L	L	VBQPZ	B
FDQ	V	G	G	JHK	B
KJTHG	M	DBJFC	B	P	F
QBJ	Q	CFG	G	GQT	D
GXF	G	Q	G	L	T
ZMWHN	R	DTNCK	D	DHXVM	B
X	L	KDL	L	ZWLKG	G
NHF	N	M	M	L	L
GWH	B	P	P	T	T
JFGZK	K	XGK	K	BFT	B
W	W	R	W	W	W
DVS	V	DBFQP	F	RVK	K
HQRGP	R	HPZ	N	HBDKS	K
LXBTG	B	VSH	M	H	D
RLP	R	FWBTG	W	Z	Z
L	T	G	P	VKB	G
WGV	L	H	Q	T	T
FTRMW	R	Z	Z	J	C
LWBPX	P	C	M	M	M
QFR	H	RGJLT	H	LZFGN	B
CGTRM	L	XRGTK	G	PKDGW	J
CWJ	C	Q	F	ZMLPV	T
TZJLW	D	ZHD	Z	GVWEJ	K
DNC	K	VWKBX	G	WPFTX	M
Z	D	DHRKL	T	WRJ	P
C	X	HLT	T	JWB	Q
WMPTC	T	MVCBP	X	VDL	G
BDT	H	H	C	R	X
RXN	R	F	F	RGXZW	G
TKCFH	Q	ZPV	R	ZGBTW	V
KHPXR	S	P		T	T
XKCPB	L	W	W	C	N
CQDBH	D	LKZ	K	TGX	R
RCN	S	T	M	D	W
L	Q	H	V	K	B
LBZNR	Q	KFPWZ	F	VGQ	G
HWK	L	XTSBJ	D	ZGP	Z
V	P	SNW	N	W	R
L	M	SJXFG	B	LQR	R
SLN	C	H	K	KJM	L
H	W	J	J	KSX	S

HVX
D
HZT
HRS
T
MKRQJ
N
K
VTN
NVM
T
ZFP
B
FXZ
SKG
SVX
Q
VPJ
HPV
JBCLV
T
M
WCR
Z
C
WMT
P
VTB
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B
W

MCB
NQZMP
B
CSBLR
C
FMCHG
R
BLRDS
WJDVQ
CFH
DQR
CDZRF
CPQXM
B
KXNQH
B
PHC
KZP
NZPTK
VRJ
RXCHD
TQCWK
WDSQR
MXHNC
W
N
R
F
WXT
ZDKTL

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F
W
C

HGRNB
N
NJLXS
CWP
K
FDCLR
FTDMG
WVT
NPDLR
PNC
DLXKT
BCGNQ
H
LNZ
QGW
V
W
B
F
ZWXNP
XJWTC
FPC
VMR
NPTVW
J
HNMCD
HXQRD
XCTZM
DNS
FVNLK

B
N
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C
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T
V
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D
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K
K

Appendix C: Stimuli for Category Matching Task

Category	Exemplar	Category	Exemplar
clothing	pants	furniture	nightstand
animals	table	sports	canoeing
clothing	tennis	sports	fishing
clothing	coat	fruit	grapefruit
fruit	dresser	animals	orange
furniture	bed	furniture	lime
sports	football	clothing	ringuette
furniture	grape	furniture	sweater
sports	basketball	clothing	eagle
sports	lamp	animals	stool
fruit	pear	furniture	diving
fruit	dress	animals	sheep
animals	elephant	fruit	lemon
furniture	shoes	sports	raquetball
fruit	cherry	fruit	cabinet
clothing	cat	animals	bird
sports	plum	animals	tie
sports	swimming	fruit	boots
furniture	dinette	sports	fridge
sports	mittens	animals	skiing
furniture	hockey	sports	coconut
sports	golf	sports	bowling
fruit	peach	fruit	kiwi
animals	socks	fruit	waterpolo
animals	dog	animals	pineapple
fruit	apple	fruit	zebra
sports	pig	animals	rabbit
furniture	tiger	fruit	avocado
fruit	soccer	sports	gloves
furniture	desk	sports	raccoon
animals	lion	furniture	camel
clothing	skirt	furniture	stove
furniture	couch	clothing	shelf
clothing	blouse	animals	squirrel
furniture	chair	clothing	raincoat
clothing	shorts	clothing	blueberries
clothing	sofa	furniture	otter
clothing	vest	clothing	goat
animals	baseball	furniture	chandelier
clothing	banana	furniture	honeydew
fruit	cow	clothing	scarf

clothing
animals
furniture
clothing
clothing
animals
sports
furniture
sports
fruit
fruit
animals
fruit
animals
sports
fruit
animals
sports
sports
fruit
animals
sports
animals
fruit
animals
fruit
furniture
fruit
sports

nectarine
snowsuit
recliner
jacket
underwear
cheetah
squash
whale
waterskiing
raisins
crocodile
parka
barstool
bear
crabapple
blackberries
longjohns
camping
snake
pantyhose
antelope
surfing
pincherry
raspberries
groundhog
strawberries
microwave
crinoline
bookshelf

sports
furniture
clothing
clothing
furniture
animals
clothing
furniture
clothing
clothing
furniture
clothing
clothing
furniture
furniture
clothing
animals
animals
furniture
sports
fruit
sports
fruit
animals
animals
fruit
furniture
animals
fruit
sports

caribou
cricket
rhinoceros
wallunit
fox
seal
belt
toaster
hippopotamus
kilt
loveseat
cape
hat
sweatpants
stereo
skating
melon
bathingsuit
curling
muskrat
shotput
dates
commode
donkey
gooseberry
sofa
gazelle
gliding
moose

Appendix D: Stimuli for Synonym-Antonym Task

First Word	Target Word	First Word	Target Word
simple	easy	get	retrieve
up	down	peak	valley
quick	fast	switch	change
near	far	wash	clean
cost	price	earth	ground
idea	thought	man	woman
shut	open	up	skyward
fast	slow	private	public
sure	certain	under	below
hot	cold	take	give
pull	push	harvest	sow
bad	evil	play	work
little	small	fat	skinny
poor	rich	pants	trousers
attempt	try	smile	frown
wrong	right	blanket	cover
order	command	hat	cap
noisy	loud	buy	sell
end	finish	mute	silent
deep	shallow	help	hinder
sorrow	grief	paradise	heaven
ill	sick	maternal	motherly
big	large	hire	fire
choice	option	pebble	stone
possess	own	penalty	punishment
early	late	rent	own
narrow	wide	round	square
mend	fix	treat	reward
listen	hear	peace	quiet
feel	sense	acquire	receive
above	below	confuse	explain
love	care	poach	steal
hate	despise	poke	prod
after	before	hide	expose
heavy	light	expand	contract
die	live	cut	tear
touch	feel	life	death
short	tall	increase	decrease
happy	sad	east	west
spend	save	stream	brook
lift	raise	murder	kill

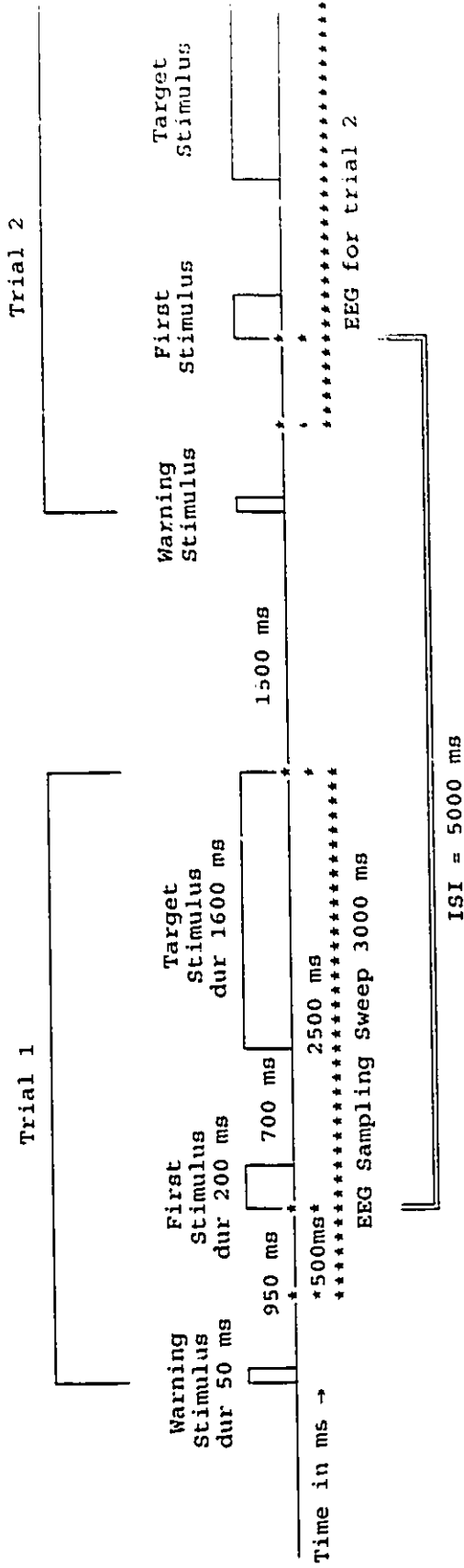
paternal
help
north
slap
expensive
dig
press
marry
siren
slip
smile
domestic
enter
hard
speak
canine
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accuse
low
agree
aged
carry
sprout
pull
call
stay
throw
noisy
border

father
aid
south
hit
costly
fill
push
divorce
horn
fall
grin
wild
exit
soft
talk
feline
bottom
acquit
high
differ
youthful
drop
wither
tow
shout
go
toss
calm
center

catch
clean
cart
casual
height
frugal
cloudy
light
charter
console
windy
cool
copy
decipher
danger
curse
success
hide
ditch
doubt
home
dwell
dynasty
restless
rob
vigour
ashes
embrace
always

release
dirty
wagon
leisurely
depth
thrifty
clear
dark
rent
harass
breezy
warm
original
interpret
safety
bless
failure
display
trench
faith
domain
live
empire
calm
steal
laziness
embers
hold
never

Appendix E: Timing for the Presentation of Stimuli and ERP Recording



The centre line represents time in ms (1000ms = 1"). The solid boxes above the time line indicate the times that stimuli are being presented. The duration of presentation is indicated by the length of the box and precise times are indicated in text above the box. The starred box below the time line indicates the times when EEG is being sampled.