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The study of behaviour, and of the mind, cannot be described

by drawing three arrows on a piece of paper.

- Emanuel Donchin

Intelligence and Event-related Potentials in a Backward-masked Auditory Discrimination Task: Analysis of Speed and Stages of Information Processing

by

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Abstract

The relation between speed of auditory discrimination and intelligence was investigated. Thirty-six females in experiment 1 and 24 in experiment 2 completed the Multidimensional Aptitude Battery (MAB: Jackson, 1984). Subjects were divided into higher (HA) and lower (LA) ability groups. An auditory oddball paradigm was employed, with the addition of a masking stimulus (1000 Hz, 55 ms duration) following the standard (600 Hz, 25 ms) and deviant (700 Hz, 25 ms) tones. The interval between standard or deviant offset and masking tone onset, the stimulus onset asynchrony (SOA), was varied at 150, 50 and 25 ms. The auditory discrimination task was presented in a passive condition in which participants ignored the tones while reading a book and in an active condition wherein they detected the deviant tone. The passive condition generated the mismatch negativity (MMN), an event-related potential measure that indexes the operation of echoic memory. The active condition produced behavioural data and P3, an ERP measure associated with stimulus evaluation and classification. In both experiments, HA participants detected more deviant tones, and had faster and less variable reaction times. Overall, P3 amplitude was significantly larger for HA subjects, with some differences in P3 latency observed. The HA group had larger MMN amplitude in the first study only; shorter MMN latencies for the HA group were observed in study 2 only. An intensity manipulation in experiment 2, intended to manipulate task difficulty, produced no graded changes in any of the variables. Results for both experiments were combined to increase power and facilitate interpretation. Overall, results indicate that more intelligent individuals process information in short-term memory more rapidly than those of lower-ability; results also suggest that speed of processing in echoic memory may underlie ability-related differences in performance.

Introduction

The past few decades have seen significant progress in our understanding of individual differences in mental ability through the application of cognitive information processing models and methods. Perhaps the most notable result of this research is the well-established link between higher intelligence and faster speed of information processing (SIP). The most consistent results have been in the area of behavioural reaction time (RT), where faster RT is associated with higher intelligence across an extensive array of elementary cognitive tasks (ECTs: Jensen & Vernon, 1986; Vernon & Mori, 1992).

Another behavioural index of SIP that has shown impressive results is inspection time (IT). Inspection time is defined as the minimum duration of exposure that is required for subjects to accurately discriminate between two stimuli which are easily discernible at longer exposure durations, e.g., the frequency of two tones. Typically, a backward masking procedure is used in which the figures or tones that are discriminated are followed by a stimulus that renders the discrimination more difficult. Individuals of higher ability are better able to make accurate judgements of, for example, pitch, as the difference in tones becomes increasingly difficult to discern (Deary, 1980).

Raz and his colleagues (Raz, Willerman, Ingmundson, & Hanlon, 1983; Raz & Willerman, 1985), in a series of behavioural studies employing a paradigm analogous to, but distinct from, the IT task also illustrated superior performance by those of higher intelligence. Unfortunately, and somewhat surprisingly given the magnitude of the correlations, attempts at replication have not been forthcoming.

Taken together, RT and IT studies indicate that highly intelligent individuals are able to make decisions of a cognitive nature more rapidly than those of lower ability. Ability-related differences in SIP in these tasks are assumed to occur in STM. Proponents of IT tasks attempt to make further inferences about pre-cognitive, sensory processes. Because most IT studies, however, make these assumptions based solely on behavioural performance and task parameters, the link between SIP, performance, and the operation of sensory mechanisms is speculative at best, and the conclusions drawn are sometimes dubious.

One field of research, however, cognitive psychophysiology employing event-related potentials (ERPs), is ideally suited to shedding light on processes of mental chronometry at all stages of information processing. For example, a growing body of evidence demonstrates a consistent negative relation between cognitive ability and the latency of the P3 component of the ERP. P3 indexes the amount of time required for stimulus evaluation in STM in simple task processes (Kutas, McCarthy, & Donchin, 1977; Magliero, Bashore, Coles, & Donchin, 1984), and varies inversely with ability (McGarry-Roberts, Stelmack, & Campbell, 1992). These relations have been observed across a wide variety of elementary cognitive tasks (ECTs).

Studies utilizing the auditory oddball task, a widely-used procedure for eliciting the P3 component, are prevalent in research relating intelligence and SIP. The oddball task involves presenting a series of "standard" tones with a particular frequency of occurrence (typically 85%). Embedded within the series of standards are tones that deviate from the standard along some dimension (e.g., pitch or intensity). These deviants typically occur with a frequency of 15%. The subject is required to discriminate the standards and deviants by indicating, usually by a button-press, when the deviant occurs within the stream of stimuli. In general, studies have reported better performance, faster P3 latencies, and larger P3 amplitudes for higher-ability participants (though smaller amplitudes are observed in some cases).

Thus, auditory discrimination paradigms like the auditory oddball have demonstrated significant relations between cognitive ability, behavioural results, and ERPs. IT-type studies, too, have shown great promise in relating sensory discrimination and intelligence. The small number employing ERPs within IT tasks, have reported results that are often conflicting.

From ERP recordings, an index of sensory discrimination, termed mismatch negativity (MMN), is derived that is relatively uninfluenced by the effects of attention, cognitive strategy, or task difficulty (Naatanen, Gaillard & Mantysalo, 1978). When ERP waveforms evoked by tones that occur frequently in a series are subtracted from ERP waveforms evoked by stimuli that occur infrequently in the series, a negative wave, the MMN, can be seen to develop, indicating that the infrequent tone was discriminated from the frequent tones. This effect is observed whether or not the observer actively listens to the tones or sits passively reading a book. In fact, an MMN can be evoked even if the observer fails to consciously detect (misses) the infrequent tone (Naatanen, Simpson & Loveless, 1982).

Thus, in its application to an auditory discrimination paradigm, this ERP measure can obviate criticisms that claim such measures are susceptible to the influence of attention deployment, motivation, or cognitive strategies. The functional significance of MMN, as well as the neural generators of MMN, have been extensively explored and therefore can yield important new information concerning the nature of the processes that contribute to variation in mental ability. The effects of auditory backward masking on the MMN wave were introduced by Winkler and Naatanen (1992) as a new way to study the neuropsychological basis of sensory memory in humans. Their stimulus presentation procedures were followed in the present study except that the intensity of the tones was increased.

Literature Review

Intelligence and Psychometric g

That people differ in their ability to complete various cognitive or intellectual tasks is self-evident. In contrast, a "satisfactory definition of intelligence or mental ability (is) elusive" (Carroll, 1993a, p.35). Jensen (1998), too, notes that " the word 'intelligence' ... has proved to be either undefineable or arbitrarily defined without a scientifically acceptable degree of consensus" (p.45). Both Carroll (1993a) and Jensen (1998) prefer the terms mental or cognitive abilities; both, too, agree that "abilities" refer to both general and specific capacities of the individual. For the purpose of the present paper, however, the terms intelligence, mental ability, and cognitive ability will be used synonymously.

Most researchers acknowledge that intelligence is best described hierarchically (Brody, 2000; Deary, 2000; Jensen, 1998). In Carroll's exhaustive compendium and reanalysis of 460 factor analytic studies spanning the 20th century (Carroll, 1993a), he elucidates a three-stratum model of intelligence. General intelligence, or "g", is located at the apex of the hierarchy. Below g are 7 broad ability factors: fluid intelligence, crystallized intelligence, general memory and learning, broad retrieval ability, broad cognitive speediness, processing speed (also referred to as reaction time decision speed), broad visual perception, and broad auditory perception.

Within the domain of abilities of auditory reception, Carroll notes that no less than 12 "linearly independent factors of individual differences in auditory receptive ability" can be reliably identified (1993a, p.392). Among these are: hearing acuity; speech sound discrimination; discrimination of tones or tone sequences with respect to attributes like pitch, intensity, duration, and rhythm; judgements of complex relations among tonal patterns; tonal imagery (associated with melodic and musical tonal patterns): discrimination of tonal patterns with respect to tempo and phrasing; speech perception under distortion; temporal tracking; absolute pitch ability.

The Biological Foundations of Psychometric Intelligence

The view that biological characteristics of the brain and nervous system are associated with individual differences in intelligence, as measured by standardized tests, has an extensive history in psychology. Galton's attempts to explain individual differences in human cognitive ability predate and anticipate psychometric conceptions of intelligence by many years. Some historians of psychology suggest that psychometric definitions of intelligence grew out of the need to systematize early biological studies of ability (Boring, 1950).

Perhaps the most influential event in the study of the biology of intelligence was the establishment of Wundt's laboratory in Liepzig, Germany in 1879. Wundt's introduction of methodologies from experimental science, particularly from physiology, launched psychology as the science of the human mind and behaviour (Wundt, 1874). His adoption, and adaptation, of such measures as reaction time, psychophysical methods such as sensory thresholds and motor facility, and his stress on quantification of variables foreheralded much of present-day psychology.

Speed of Responding: Reaction Time

Both Galton and Wundt reported substantial individual differences in RT in various simple tasks. These reports foreshadowed recent developments that demonstrate the relation between SIP and intelligence. In an extensive review of the relation between RT paradigms and psychometric intelligence, Jensen (1982) highlights several key points. One is the extreme rarity of positive RT – intelligence correlations in the extant literature. Though a small proportion of studies show small or "unimpressive" correlations, all studies show correlations in the expected direction, with higher ability individuals having faster RTs than low ability subjects. Many studies have confirmed this conclusion (Jensen, 1982; Jensen & Munro, 1982; Vernon, 1990; Vernon & Mori, 1992).

Jensen also notes that intra-individual variability in RT as indexed by the standard deviation of RTs for an individual across trials within an experimental condition (SDrt) has proven to be the best overall correlate of psychometric ability, with correlations ranging from -.30 to -.45 (Jensen, 1982, p.114). Overall, the inverse relation between RT and greater intelligence, and between SDrt and intelligence, together comprise the most robust findings in the entire literature of differential cognitive ability.

Inspection Time

Inspection time (Nettlebeck & Lally, 1976; Vickers, 1970, 1979; Vickers, Nettlebeck, & Willson, 1972) is defined as the threshold exposure duration required for a stimulus to be encoded to a sufficient degree so that a discrimination task can be successfully performed. Typically, two lines of varying length are presented for very brief durations. The subject is required to correctly identify the longer line. A backward masking stimulus immediately following the stimulus presentation limits post-presentation processing (Nettlebeck, 1987). Accuracy rather than speed instructions are emphasized. Target exposure duration, that is, the duration between target onset and mask onset (also referred to as SOA) is varied until response accuracy falls below a predefined level (typically 97.5%). IT paradigms using visual, auditory, and tactile modalities are possible (Kranzler & Jensen, 1989).

IT and Intelligence

Inspection time is considered to reflect individual differences in speed of apprehension, or "speed of perceptual intake" (Caryl, 1994, p. 17). It is operationalized using a discriminative task that requires subjects to determine which of two visual patterns that are immediately followed by masking stimuli were presented. The derived variable, which is an estimate of the minimum tone duration at which a subject can discriminate between two patterns, is then correlated with intelligence test scores (Nettlebeck & Lally, 1976). The general finding has been that subjects of higher intelligence make accurate decisions at shorter stimulus durations than those of lower ability. The interpretation is that the more highly intelligent subject requires less time to extract the information upon which the discrimination (e.g., "left is longer") is based.

An early review by Brand and Deary (1982) examined nine studies conducted between 1976 and 1980. Over a broad range of IQ (44 – 138), significant negative correlations averaging .77 were reported. Nettlebeck (1987) also conducted an extensive review of IT and intelligence, concluding that a correlation of -.50 after correction for attenuation represents the best overall estimate of the relationship. In a comprehensive meta-analysis, Kranzler and Jensen (1989) collected results from several unpublished thesis studies (honours to doctoral) in addition to those formerly cited in the literature. Where possible, they divided studies into correlates of IT and general IQ, performance IQ, and verbal IQ. Using a stringent criteria for excluding studies not amenable to their procedure, they found correlations of -.56, -.74, and -.38, respectively, after correction for artifactual effects. These results were for normal adults.

The fundamental nature of the IT effect, associating mental ability with the speed with which discriminations are made, has not gone unchallenged (White, 1993, 1996). Some authors have argued that performance characteristics such as individual differences in attention deployment, persistence, facility with ECTs, or the ability to devise strategies that facilitate performance may mediate the discrimination effects. In addition to these measurement issues that challenge the validity of the IT measure, the functional significance of the effect is widely debated. In one view, IT is regarded as an index of the efficiency of post-sensory processing, with decreasing target stimuli duration and the backward mask serving to determine whether there was sufficient time for the target to be transferred from echoic (or iconic) memory to STM and subsequently discriminated (White, 1993, 1996). Another view holds that IT is a measure of the temporal resolution of sensory processing. From this perspective, decreasing target duration and backward masking serve to determine whether there was sufficient time to resolve the target stimulus or whether the target and the mask are integrated and thus indistinguishable (White, 1993, 1996). In general, both theoretical and methodological issues remain unresolved.

Auditory Discrimination Tasks

Studies on auditory frequency or pitch discrimination have been used to examine a diverse array of psychological phenomena, and have shown impressive results in research on intelligence when the discrimination between tones is easy, that is, in the absence of experimental manipulations rendering the discrimination difficult. Typically, the manipulation involves some form of backward masking of the tone or tones to be discriminated. Much of this research has been informed by the seminal behavioural studies by Massaro (1970, 1972a, 1972b, 1973a, 1973b).

Massaro and Auditory Backward Masking

In a series of studies, Massaro (1970, 1972a, 1972b, 1973a, 1973b) introduced backward and forward masking to the study of "preperceptual auditory images" (1970, p.41). Massaro maintains that "perception or perceptual processing can be thought of as an analysis of the sensory input in which features are detected that correspond to encoded features in memory. When a sufficient number of features are found in the sensory input that correspond to the features of the item in memory, the stimulus is recognized as that item" (1970, p.42). This conclusion, in fact, comprises part of the rationale for the original IT task (Nettelbeck & Lally, 1976). Because feature detection is temporally dependent, Massaro (1970) proposed that a sensory memory store of some kind could hold the sensory experience after the stimulus is terminated. But the contents of this iconic or echoic buffer can be overwritten by terminating the feature-detection process at different times after a short stimulus is presented. Masking stimuli presented immediately after the stimulus overwrite or otherwise degrade the contents of the buffer.

The basic paradigm entails a very brief high (870 Hz, 20 ms duration, 81 dB) or low (870 Hz, 20 ms duration, 81 dB) frequency tone presented to test subjects on each trial: participants were then instructed to identify the tone as being high or low in pitch. Raz et al. (1983, 1985) note that participants had no difficulty performing this task, given a sufficient frequency difference between the high and low tones. In other words, the task itself was straightforward, even easy. However, when the test tone was followed at varying intervals by a backward masking tone, discrimination performance decreased significantly (the masking tone was 820 Hz, 500 ms duration, 81 dB, and followed the test tone at SOAs of 0, 20, 40, 80, 160, 250, 350, or 500 ms).

This identical paradigm, in fact, was adopted (and later adapted) by Raz et al. (1983, 1985) as the basis of a series of studies on auditory discrimination and intelligence. They noted that Massaro's performance curves , which plotted percent correct detections as a function of intertone interval, were highly suggestive of individual differences in ability. Two studies are particularly relevant. In Massaro's initial study (1970), the performance of 3 subjects remained fixed at roughly 100, 90, and 80%, respectively at SOAs of about 250 ms or greater: at much shorter SOAs (between 0 and 40 ms), performance dropped to approximately 80, 70, and 60%.

respectively. In a subsequent study (Massaro (1973a). Massaro divided 15 university undergraduates into "best", "worst", and "middle" performance groups. Now the discrimination was made more difficult. Test tones (20 ms duration, 76 dB, 1000 Hz) differed only in whether they were sine or sawtooth waves: the mask was also 1000 Hz (20 ms duration, 76 dB), and consisted of alternating sine and sawtooth components. At SOAs ranging from 480 to 140 ms, performance of the "best" group was about 95%; as SOAs decreased to 40 or 20 ms, performance remained fixed at 85%; at 0 ms SOA, individuals still performed with about 80% accuracy. For the "middle" group, subjects performed at 85, 78, 70% accuracy across the same 3 SOA ranges (480 to 120 ms, 40 to 20 ms, and 0 ms). For the "worst" group, accuracy for the 3 SOA ranges was 75, 65, and 60%, respectively.

Massaro (1970, 1971) hypothesized that the systematic decrease in performance was due to the masking tone's interference with perceptual processing of the auditory image of the test tone. Massaro (1970, 1972a, 1972b, 1973a) determined that by varying the "silent interval" between the test and masking tone, that is, by varying the SOA, it was possible to determine the mental chronometry of perceptual processing of the sensory image of the test tone." (1970, p.411). (This, of course, is what auditory inspection time (AIT) studies purport to do. More importantly, it is what ERPs studies are well-equipped to do.)

These studies demonstrate that even at very long SOAs when the backward mask did not interfere with processing, performance was fixed at less than 100% by some characteristic of the individual. Moreover, at very short SOAs , and even when the mask immediately followed the target offset, some subjects maintained a very high level of performance.

In the terminology of differential psychology, the most likely candidate in this regard is intelligence.

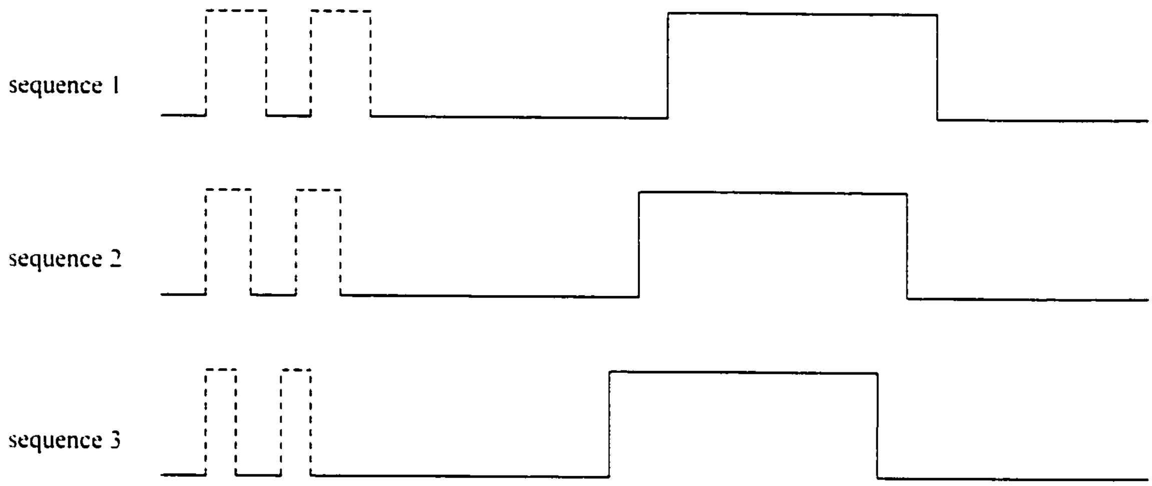
Auditory IT

Auditory IT (AIT) is defined as the minimum tone duration at which subjects are able to correctly identify to some predetermined level of accuracy the temporal order of two tones of markedly different frequencies, and which are immediately followed by white noise (Brand & Deary, 1982). An important issue is the distinction between AIT as it has been defined and as it has been measured. In practice, several operational definitions of AIT have been employed.

Brand and Deary (1982) introduced the first operationalization of the AIT task. This task involves identifying the temporal order of 2 consecutive tones differing in frequency. The order of the 2 tones is varied randomly and the 2 tones are followed by a masking tone of constant frequency. Duration between the offset of the second tone and the onset of the masking tone is also constant, that is, varying SOAs are not used in this paradigm. What does vary is the duration of the 2 tones. As the duration of the tones decreases, discrimination becomes increasingly difficult. Though this too clearly assesses IT in the theoretical sense, the operationalization, that is, IT as measured, is quite different. The general timing sequence, characteristics, and results of AIT studies are presented in Figure 1.

Figure 1

General Timing Sequence for Auditory Inspection Time Task



Characteristics:

- Stimulus pairs
- *Duration* of stimuli *varied* (dashed lines)
- Mask follows stimuli at *constant* ISI
- Participant determines whether the 1st or 2nd tone is higher or lower in pitch

Results:

- Higher ability participants are better able to discriminate tones
- Higher ability participant's performance remains high even at very short tone durations
- Correlations between intelligence and discrimination threshold of .30 to .50

Frequency Discrimination: The Raz Paradigm

Raz et al. (Raz, Willerman, Ingmundson, & Hanlon, 1983; Raz & Willerman, 1985) introduced an auditory discrimination task based on the work of Massaro (1970, 1972a, 1972b). Unlike the auditory IT task of Deary et al., the paradigm employed varying SOAs and stimuli of constant duration. The general timing sequence, characteristics, and overall results of the studies are presented in Figure 2; note that only a single target stimuli (which is then followed by the mask) is presented in each trial.

In experiment 1 (1983), 14 participants were divided into high ability (HA) and low ability (LA) groups on the basis of Scholastic Aptitude Test (SAT) scores. In strict accordance with Massaro's (1970) paradigm, higher (870 Hz, 20 ms duration) and lower (770 Hz, 20 ms) frequency target tones were presented; the masking tone (820 Hz, 500 ms duration) followed the target tone at thirteen SOAs (0, 10, 20, 30, 40, 60, 80, 120, 160, 250, 350, 500, and 1000 ms). All tones were 81 dB. Results indicated that subjects in the high-SAT group had significantly superior performance than individuals in the low-SAT group, and that these differences were especially apparent at short SOAs. Specifically, a correlation of -.53 ($p < .05$) between SAT groups and threshold SOA (i.e., the calculated SOA at which performance for the respective groups dropped to just below 75%; thresholds SOAs were logarithmically transformed for the correlational analysis) was reported. Median threshold SOAs for the high and low SAT groups were 16.6 and 67.8 ms, respectively. Moreover, performance curves indicated that proportion correct remained slightly above 50% for the low SAT group and above 60% for the high SAT group at 0 ms SOA.

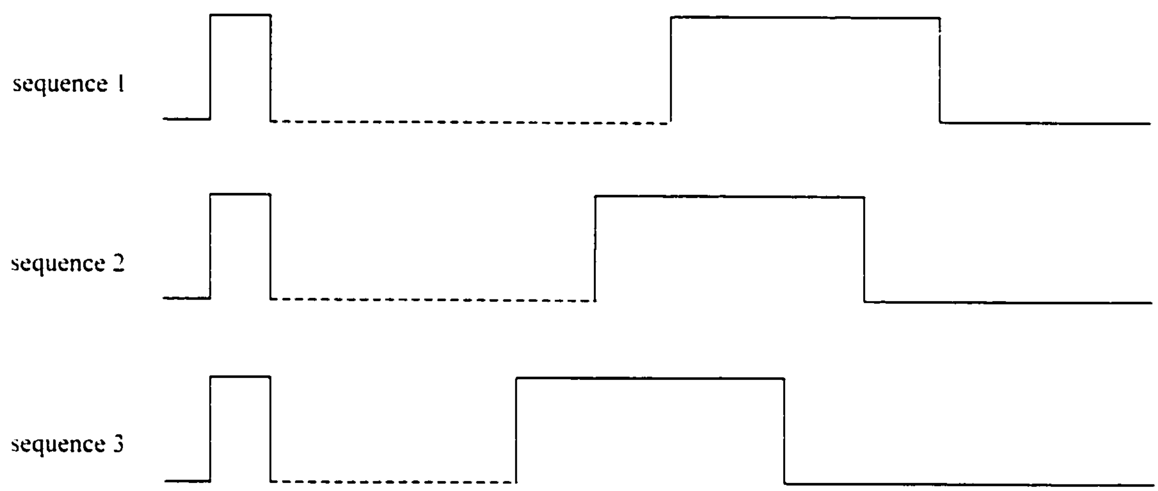
In the second experiment, 20 participants were grouped by scores on the Cattell Culture Fair Intelligence Test (Cattell & Cattell, 1959). Six SOAs were used (0, 10, 20, 70, 120, 250 ms) and target tone durations were varied at 20 or 30 ms. Subjects underwent more extensive practice (75% accuracy at 250 ms SOA at both 20 and 30 ms target tone durations: they point out that all subjects attained 90% accuracy during practice). and now corrective feedback was provided on-line. Again. HA group performance was better at all SOAs and for both durations. and HA subjects superior performance was particularly evident at shorter SOAs. Notably. Ss classified as being of high ability could make accurate discriminations at SOAs of 0 ms. that is. when the masking stimulus immediately followed the target and when the duration of the tone to be discriminated was either 30 or 20 ms. Lower ability participants had threshold SOAs of34 ms for the 20 ms tone duration and 13.6 ms for the 20 ms duration. The resulting correlation between intelligence and logarithmically transformed threshold SOA was -.73 ($p<.05$) and -.69 ($p<.05$) at 30 and 20 ms tone durations. respectively.

These results were replicated and extended by Raz et al. in a subsequent experiment using a larger sample (Raz & Willerman. 1985). Thirty-six participants were grouped by SAT Cattell Culture Fair Intelligence Test (Cattell & Cattell. 1959) scores. Now. tone durations were varied at 10. 13. and 20 ms. Stimulus onset asynchronies were 0. 20. 30. 60. 120. and 480 ms. Subjects were instructed to ignore the tone durations and indicate whether the tone was high or low. Cattell IQ scores correlated with (logarithmically transformed) threshold SOA at -.47. -.44. and -.53 for 10. 13. and 20 ms tone durations.

In spite of these results. no other studies have employed this paradigm. Given the magnitude of the correlations. this is somewhat surprising. The experimental effect of variable SOAs. as opposed to variable stimulus durations (with the masking stimulus at a constant ISI) is unique in the intelligence literature. and. in contrast with the AIT paradigm. builds on the substantial research program of Massaro (1970. 1972a. 1972b. 1973a. 1973b).

Figure 2

General Timing Sequence for Auditory Discrimination Task (Raz et al., 1983, 1985)



Characteristics:

- Single stimulus
- *Duration* of stimuli *constant*
- Mask follows stimuli at *variable* SOA (dashed lines)
- Participant determines whether the tone is higher or lower in pitch

Results:

- Higher ability participants better able to discriminate tones
- Higher ability participant's performance remains high even at very short SOAs
- Correlations between intelligence and discrimination threshold of .30 to .70

Event-related Potentials and Intelligence

The mid- to late-1960s marked the introduction of both EEG (Ellingson, 1966; Giannitrapani, 1969) and ERP (Chalke & Ertl, 1965; Rhodes, Dustman & Beck, 1969; Vogel & Brogerman, 1964, 1966; Weinberg, 1969) techniques to the study of intelligence.

Event-related Potentials

Electroencephalographic (EEG) waveforms record the ongoing bioelectric activity of the brain. ERPs are derived by averaging EEG activity that is time-locked to a series of repetitive stimulus presentations. ERPs are used to provide electrophysiological indices of neuronal cognitive processes. By averaging EEG activity during stimulus events, the bioelectric activity that is not related to the processing of the stimulus is removed. The resultant waveform is a composite of negative and positive peaks, which are identified by their polarity and latency. Amplitude, measured in microvolts, is defined as the vertical deviation of the waveform from a baseline index. Latency is defined as the time in milliseconds from the onset of the eliciting event to the component's peak amplitude. The N100 component, for example, is a negative-going peak with an modal latency of 100 ms after stimulus onset. Although both base-to-peak and peak-to-peak measures are possible, base-to-peak indices are more commonly used.

Once a component has been identified, cognitive psychophysiological paradigms are engaged, the purposes of which are to explicate the cognitive operations manifested and to elucidate its parameters (Donchin, 1981). To this endeavor we can add explication of the effect of individual differences in intelligence on these components.

Exogenous (Sensory) ERP Waveforms

Sensory or exogenous ERP waves are elicited by repetitive stimulation of visual, auditory, and somatosensory modalities (Angel, Boylls, & Weinrich, 1984; Eisen & Elleker, 1980). Simple reversals of visual pattern can also generate exogenous ERPs (Cobb & Dawson. 1960: Harter & White. 1970). The amplitude and latency of the resultant waveforms. which develop in the 100 to 200 ms range. are influenced solely by physical characteristics of the external eliciting stimuli (Coles. Gratton & Fabiani. 1990: Donchin. Ritter & McCallum. 1978). The most widely researched of these early components is the N1 – P2 complex. This component is believed to signal the arrival of sensory input at the cortex.

Ertl (Barry & Ertl. 1966: Chalke & Ertl. 1965: Ertl & Schafer. 1969). along with other researchers (e.g.. Perry. McCow. Cunningham. Falgout. & Street. 1976: Shucard & Horn. 1972) found negative correlations of about .30 between the latency of ERP waves elicited by punctate visual stimuli and intelligence. Attempts at replication have met with failure (Barrett & Eysenck. 1994: Davis. 1971: Dustman & Beck. 1972: Shucard & Callaway. 1973: Rhodes. Dustman. & Beck. 1969: Widaman. Carlson. Saetermore. & Galbraith. 1993) more often than success (Federico. 1984: Josiassen. Shagass. Roemer. & Slepner. 1988: Robinson. Haier. Braden. & Krengel. 1984).

Other proposed relations between ERP components and intelligence have included counting the number of times the ERP trace crosses the zero-point within a particular time epoch. (Weiss. 1986) and measuring the slope of waveform components (Morris & Alcorn. 1995). A proposed association between intelligence and N140-P200 peak-to-peak amplitude has also been studied. with inconclusive results (Haier. Robinson. Braden. & Williams. 1983: Robinson. Haier. Braden. & Krengel. 1984: Stough. Nettlebeck. & Cooper. 1990). Widely disparate findings are common. even when apparently identical measures and procedures are used (Barrett & Eysenck. 1994: Bates & Eysenck. 1993: Shagass. Roemer. Straumanis. & Josiassen. 1981: Vogel. Kruger. Schalt. Schnobel. & Hassling. 1987).

The string measure (A. E. Hendrickson. 1982; D. E. Hendrickson. 1982; Blinkhorn & Hendrickson. 1982; Stough. Nettlebeck. & Cooper. 1990). a measure of waveform complexity. has also received considerable attention. Considered a measure of neural efficiency. Hendrickson at al. posit that higher ability subjects have lower error rates when information is coded and processed. They speculate that neuronal circuitry allowing a high degree of stimulus fidelity is concurrent with error-free information transmission and memory storage. Individuals with neural circuits of higher integrity would be better equipped to process. store. and access information and would do so more rapidly. Ostensibly this results in more complex components because the large number of waveforms required for the averaging process have more pronounced and stable peaks and troughs. Attempts at replication have been indeterminate. however. Upon reanalysis of Blinkhorn and Hendrickson's data. some researchers have reported significantly smaller correlations (Haier. Robinson. Braden. & Williams. 1983). correlations opposite in sign (Vetterly & Furedy. 1985). and no consistent relationship found (Robinson. 1997; Vogel. Kruger. Schalt. Schnobel. & Hassling. 1987). Correlations between the string measure and verbal indices of IQ. apparent in some studies. are absent in others: the same effect is observed with Raven's Progressive Matrices (Raven. 1958). where significant correlations are present in only some investigations (Eysenck. 1993).

Moreover. and more importantly. the functional significance of the Hendrickson string measure is far from clear. String measures are obtained in conditions where no intellectual demands are places on the subject. A compelling explication of why higher ability subjects should exhibit waveforms with lower complexity. particularly when no cognitive processing is being performed by the subject. is still forthcoming.

A further important caveat regarding these techniques is that they are not used outside the domain of intelligence. In short, the functional significance of the measures themselves is obscure. It is reasonable to assume that use of the established methods of amplitude and latency analysis would be more fruitful in the study of the psychophysiology of intelligence. Overall, the relation between early sensory components and intelligence is doubtful (Stelmack & Houlihan, 1995).

Endogenous (cognitive) ERP Waveforms

In contrast to exogenous sensory ERP waveforms that are determined primarily by external physical stimulation, endogenous cognitive components are determined primarily by intrinsic psychological activity (e.g., stimulus evaluation or classification, short-term or long-term memory scanning). They may be obtained by involving the subject in a memory task. They require cognitive information processing on the part of the subject (Duncan-Johnson & Donchin, 1982), and can be elicited by the absence of expected stimuli (Sutton, Braren, Zubin, & John, 1965).

Endogenous (cognitive) ERP Waveforms and Intelligence

A standard procedure in research relating ERP waves and intelligence involves correlating amplitude and latency measures with intelligence test and subtest scores. Elementary cognitive tasks (ECTs) are performed concurrently with ERP recording. Mental ability is assessed independently then correlated with the ERP components at a later time. Deary and Caryl (1994), in a review of the literature, conclude that P3 latency and P3 amplitude showed the most consistent association with intelligence. This literature, as well as more recent work, will be reviewed later in this text.

The P3 Component of the ERP Waveform

The P3 component of the ERP waveform has been shown to be a reliable index of the detection, recognition, and classification of target stimuli (Polich & Kok, 1995; Segalowitz, Unsal, & Dywan, 1992). More specifically, it indexes the speed of stimulus classification and decision-making processes (Kutas, McCarthy, & Donchin, 1977; Magliero, Bashore, Coles, & Donchin, 1984). It is, perhaps, the most widely-used, reliable, and informative measure of mental chronometry in the cognitive psychophysiology literature. Test-retest reliability of the P300 across various time intervals is high, with one study showing a reliability index of .74 across 2 years (Segalowitz & Barnes, 1992). Within study indices are in the .80 to .90 range (Fabiani, Gratton, Karis, & Donchin, 1987). P3 has also been shown to have high heritability (Katsanas, Iacono, McGue, & Carlson, 1997). The medial temporal lobe, particularly the temporal-parietal junction in the case of auditory stimuli (Knight, Scabini, Woods, & Clayworth, 1989), and hippocampus are involved in its production (McCarthy, Wood, Williamson, & Spencer, 1989).

Studies utilizing the auditory oddball task to elicit P3 are common. The oddball task involves presenting a series of "standard" tones with a particular frequency of occurrence (typically 85%). Embedded in the series of standards are tones that deviate from the standard along some dimension (e.g., pitch or intensity). These deviants typically occur with a frequency of 15%. The subject is required to discriminate the standards and deviants by indicating in some way when the deviant occurs within the stream of stimuli. Because the deviants can differ from the standard in any number of ways, and by a large or small amount, task difficulty can be varied quite easily. In any case, a cognitive operation involving comparison of the two tones is performed, with latency increasing systematically with task difficulty (Polich & Martin, 1992). Responses can also be elicited by the absence of the stimuli, that is, when expected tones are omitted from the train of stimuli. When elicited by this task, P3 typically appears as a prominent component that is maximal centro-parietally (Falkenstein, Hohnsbein, & Hoorman, 1995). Though its modal latency is 300 ms, P3 is frequently observed two to three hundred ms later than this for more difficult discriminations.

Functional Significance of P3 Correlates of Intelligence: RT and P3 Latency

A substantial body of evidence identifies RT as an index of speed of processing. A similar role has been posited for P3 latency. Both P3 latency and RT increase with increasing task difficulty (McGarry-Roberts, Stelmack, & Campbell, 1992). Furthermore, P3 latency and RT have both been shown to increase with increasing set size in the Sternberg (1969) memory scanning task (McGarry-Roberts, Stelmack, & Campbell, 1992). In the Sternberg task, subjects are presented with an array of digits (letters or numbers), which appear on the computer screen for a brief period. Typical set sizes are 1 (a single digit), 3, 5 , and 7 digits. Subjects are required to hold these digits in memory. After a brief intervening period, a single digit or "probe" is presented onscreen. Subjects must respond by indicating whether the digit was or was not present in the original array. Auditory versions are also possible. Now the digits in the set are presented sequentially, followed, after a pause, by the probe. The subject responds in similar fashion.

Because P3 latency is considered an index of speed of cognitive processing in general, and speed of categorization or stimulus evaluation time, in particular, the conceptual relation to reaction time is evident (McCarthy & Donchin, 1983). It is reasonable to posit that both index some related, covarying aspect of speed of information processing. Miller (1994), for example, refers to P3 latency as "a speed measure", noting that "faster reaction times ... and shorter latencies ... represent doing the same things faster" (p.808). By virtue of this RT-ERP latency relationship, the functional significance of ERP research on P3 latency sets it apart from other attempts to relate physiological processes with intelligence.

One important caveat, however, is that RT and P3 latency index independent though covarying processes. Verleger (1997) reviewed the effects of a wide variety of experimental manipulations in P3 latency and RT, using the ratio of change in P3 latency to change in RT as an index of relative sensitivity. He found that manipulations that influenced stimulus evaluation and classification (e.g., auditory degradation, attenuation of visual and auditory intensity, and increase in number of irrelevant stimuli while randomly varying location of relevant stimuli) all strongly influenced P3 latency but had relatively small effects on RT. P3 latency was insensitive to manipulations that delayed response execution (mental rotation, mental arithmetic, response complexity, and Stroop task). Thus, while P3 latency indexes aspects of stimulus-evaluation time, it is, unlike RT, largely independent of response-selection and production (Howard & Polich, 1985).

In a study of stimulus and response compatibility, Ragot et al. (Ragot & Renault, 1981; Ragot, 1984) presented stimuli on either the left or right side of a screen. In one condition, subjects responded to stimuli presented on the right side with their right hand; in another condition, left hand responses were required for stimuli on the left side. When the stimulus and the appropriate response were on opposite sides, both RT and P3 latency increased (as compared to the same-side condition). However, when subjects were required to cross their hands over one another, only RT increased. These results indicate that although both RT and P3 latency are implicated in the decision-making process, only RT is involved in actual response production. In a pharmacological manipulation, administration of methylphenidate, a stimulant with cognitive effects, decreased mean RT and standard deviation for RT, while only decreasing standard deviation of P3 latency (Brumaghim, Klorman, Strauss, Lewine, & Goldstein, 1987). Finally, P3 latency has been shown to correlate more highly with reaction time when accuracy rather than speed instructions are given (Donchin, 1979).

Functional Significance of P3 Correlates of Intelligence: P3 Amplitude

The relation between P3 amplitude and intelligence is considerably less clear. P3 amplitude indexes the amount of information extracted by the subject during cognitive processing (Johnson, 1986; 1988b). Physiologically, larger amplitudes may be (but are not necessarily) the result of a larger population of neurons firing, the synchronization of the neurons involved in the elicitation of the ERP component, or both (Hernandez-Collados, 1995). Because higher amplitude is suggestive of greater information extraction (Johnson, 1986; 1988b), it might be posited that higher ability subjects would have higher amplitudes than lower ability individuals overall. It could also be possible, however, that subjects with higher intelligence might use their cognitive resources more efficiently, thereby reducing P3 amplitude in some conditions. This issue remains unresolved in the literature.

Early attempts at explaining the relationship between ERP amplitude measures in general, as they relate to intelligence, have been inconclusive (e.g., neural efficiency, as discussed above (A. E. Hendrickson, 1982; D. E. Hendrickson, 1982; Blinkhorn & Hendrickson, 1982), and neural adaptability (Schafer, 1979, 1982)). Neural adaptability (NA; Jensen, Schafer, & Crinella, 1981; Schafer, 1982) is reflected in the proclivity for the amplitude of ERPs to be large in response to unexpected stimuli and small in response to those that are expected. An early study (Schafer & Marcus, 1973) found that when subjects determined when a stimulus would be delivered themselves, consistently smaller ERP amplitudes were produced. The study demonstrated that these effects were more pronounced with subjects of higher intelligence.

Results were interpreted as indexing the greater adaptability of more intelligent subjects. It was argued that less neuronal energy was invested in predictable stimuli while more was invested in novel events, with the more highly intelligent individual recruiting fewer neurons for predictable stimuli than the less intelligent. Greater amplitudes in the studies of Schafer et al. were found in *all* ERP components (1979, 1982). Given the difficulties in interpretation, however, this paradigm has been largely abandoned.

Overall, conclusions regarding the functional significance of P3 amplitude are still pending. Conclusions regarding the functional significance of P3 latency, construed as a speed of information processing index complementary to RT, are fairly well-established.

Auditory Discrimination Tasks and ERPs

Auditory Oddball

As described above, the auditory oddball task involves presenting a sequence of "standard" tones with a certain frequency of occurrence (e.g., 85%). Rare tones (e.g., 15% frequency of occurrence) occur randomly within this stream of standards. These rare tones are the "oddballs". The subject's task is to discriminate the standards and deviants by some overt response.

Polich et al. (Ladish & Polich, 1989; Polich, Ehler, Otis, Mandrell, & Bloom, 1986; Polich, Howard, & Starr, 1985; Polich & Martin, 1992), in a series of experiments employing the oddball paradigm, found consistent latency effects across different indices of intelligence, with correlations in the -.35 to -.45 range (e.g., -.36 for P3 latency and grade point average (Polich & Martin, 1992)). O'Donnell, Friedman, Swearer, and Drachman (1992), assessed concordance between P3 latency in an oddball task and psychometric performance on a battery of tests. P3 latency was correlated with general intelligence and concentration in an active oddball paradigm.

In a passive oddball, wherein the subject does not make an overt response , P3 latency was found to correlate with verbal learning, narrative recall, and verbal fluency. Overall, correlations were higher in the active condition, the passive format requiring less cognitive processing on the part of the subject. Most notably, the correlation between latency and general intelligence was -.44, which was significant at the .01 level of probability.

Segalowitz, Unsal, and Dywan (1992), using a group of bright 12-year-old children as subjects (minimum IQ of 135 on the WISC-R instrument) found no significant P3 latency differences compared to normal child controls on an auditory oddball task. However, variability of both P3 latency and amplitude as indexed by the coefficient of variation (SD/M) was larger for child controls, though values failed to reach significance. Another study using child subjects (Robaey, Cansino, & Renault, 1995) and the oddball paradigm assessed P3 latency and amplitude measures at the parietal-occipital site. Correlations between 4 categorization tasks derived from the WISC-R (1981) and P3 components were in the -.30 to -.50 range (latency) and -.37 to -.43 range (amplitude). When scaled scores were used, however, only P3 amplitudes to targets were significant. It is important to note that, as in the study by Robaey et al. (1985), all subjects, referred to as normal, were of average ability; IQ score range was not given. Stauder et al. (Stauder, van der Molen, & Molenaar, 1995), also using a sample of children in an auditory oddball procedure, found that amplitude effects for a late-occurring P3 just failed to reach significance. No latency effects were reported.

IT Tasks and ERPs

A small number of experiments have examined characteristics of the P3 component within an IT paradigm. Though plagued with theoretical and methodological problems, a few of these studies have reported results that accord with current knowledge of the physiology underlying the operation of sensory and cognitive mechanisms. Alcorn and Morris (1996), for example, recorded ERPs concurrently with visual IT tasks and then correlated results with scores from the Raven's Progressive Matrices (Raven, 1958). They hypothesized that increasing task difficulty would correspond with increases in P3 latency and decreases in P3 amplitude. As discriminations became increasingly difficult, significant effects were observed for P3 amplitude but not for latency. Higher ability subjects had shorter P3 latencies and larger P3 amplitudes overall, and they maintained superior performance even in the most difficult conditions. Studies of this type, however, are very rare.

Caryl (1994), for example, summarizes studies relating intelligence, IT, and ERP measures (see also Burns, Nettelbeck, & Cooper, 2000; Caryl & Harper, 1996; Vigil i Colet et al., 1993). Caryl claims that "conventional measures of the latency and amplitude of major peaks and troughs of the ERPs have *not* been able to provide information on the precise time course of intelligence-related differences in information processing" (p. 16). This assertion is dubious in light of studies relating P3 latency with intelligence (e.g., the auditory oddball and other ECTs).

Inspection time - ERP studies can be critiqued on several grounds. The most serious criticism relates to the functional significance of the "slope" measure used. Defined by Caryl as P200T, it is the "the rise time of the P200 component" (1994, p.17), and is purported to index the speed of information transfer from the sensory buffer to STM. This is incorrect. Information is not available to STM until the individual has directed attention to the stimulus. Chronometrically, this event is demarcated by the N2b component of the ERP waveform (Naatanen & Winkler, 1999), which *follows* the N1-P2 complex. In short, it is not possible that information is transferred to STM during the time period between the peak amplitudes of N1 and P2. Moreover, with the exception of two studies by Chapman, McCrary, and Chapman (1978, 1981). the use of a slope measure for *any* ERP component is unknown in cognitive psychophysiology.

Methodologically. these studies can also be criticized on several grounds. Caryl states that P200T is "defined as the time difference (in ms) between the latency at which the rising wavefront of the P200 component cuts a suitable zero-line and the latency of the peak of the P200 component" (p. 17). What a "suitable" zero-line is remains unresolved. Moreover. the use of zero-crossings. a measure dating back to Ertl et al. (Barry & Ertl. 1966: Chalke & Ertl. 1965: Ertl & Schafer. 1969) and defined as "the mean potential over a 200 ms time window covering the P200 (from 75 to 275 ms). *or over the whole ERP*" (Caryl. 1994. p. 17) is highly questionable. and. again. unknown in the vast literature of cognitive psychophysiology.

In addition. studies of this type routinely use a single electrode located at the vertex to record 'P200T'. as well as P300. Researchers then point out that correlations between intelligence and P3 latency reported in other studies were not observed. Vertex electrode placement is appropriate for N1 and P2. but not for P3. which is maximal at the P_z electrode site (Johnson. 1988b). Finally. in the AIT task. the two target stimuli are presented in rapid succession: ERPs are likely elicited by both stimuli. The possibility that P200 and P300 are elicited by the first and second stimuli. respectively. is not addressed in these studies.

ERPs and Intelligence: Other ECTs

Digit Span

Although an early demonstration of concordance between memory capacity and P3 latency (Polich. Howard. & Starr. 1985) was criticized for failing to correctly control for effects of age (Surwillo. 1984). two subsequent studies (Howard & Polich. 1985: Polich. Ladish. & Burns. 1990) replicated and extended the previous findings. These results indicate the high degree of concordance between ability to acquire and store information in short-term memory (STM) and intelligence, on one hand, and P3 latency, on the other.

More Complex ECTs

Egan et al. (Egan, Cheswick, Santos, Nadia, Remington, & Best, 1994) found significant correlations between P3 latency and digit symbol, digit span, auditory verbal learning (immediate and delayed recall), word fluency, and 2 indices of trail-making (absolute values between .25 to .41). Concordance between amplitude and 6 intelligence subscales, namely similarities, arithmetic, verbal intelligence, logical memory (immediate and delayed recall), and one index of trail-making varied between .30 and .41 (absolute values). Full-scale IQ correlated -.28 with amplitude; no relationship between IQ (verbal, performance, or full-scale) and latency was detected. It is interesting to note that of the 3 ERP components (N1, P2, and P3) assessed in this study, 14 of the 18 correlations to reach significance were for the P3 component, supporting the position that only later cognitive components would show concordance with intelligence (Deary & Caryl, 1994). Of these, 9 were significant at probability values below .05 (5 at .025, 2 at .005, and 2 at .01). An earlier study by Egan et al. (Egan, Chiswick, Brittle, & Goodwin, 1993) using HIV-positive subjects, found similar overall results.

The Sternberg STM scanning task (S. Sternberg, 1966, 1969), exploited in a number of experimental paradigms, has also been used in ERP studies. Developed to explore the structure of information held in short-term memory (STM), the technique assesses the timing of STM searches. In the simplest format, the subject first encodes a memory set of, typically, digits. A probe item is then presented and the subject must indicate whether the probe was present in the memory set. Pelosi et al. (Pelosi, Holly, Slade, Hayward, Barrett, & Blowhard, 1992a, 1992b), using auditory Sternberg tasks, found decreasing P3 amplitude to the probe stimuli associated with higher intelligence. No latency effects were uncovered, however. McGarry-Roberts, Stelmack, and Campbell (1992), in a study employing the Sternberg task and 5 other ECTs, assessed RT and P3 latency simultaneously. Correlations of -.38 and -.32 were found for the category-matching task (which assesses speed of retrieval from long-term memory (LTM) and the Sternberg (STM digit-recognition) task, respectively. Except for the semantic similarity task (a measure of linguistic processing efficiency that assesses speed of retrieval from LTM: Posner, Boise, Iceman, & Taylor, 1969), no amplitude effects were found.

In summary, results from numerous studies using a wide variety of ECTs indicate a consistent and replicable negative relationship between P3 latency and intelligence. Results of paradigms exploring amplitude effects are more equivocal, with studies indicating positive correlations reported as often as those reporting negative concordance or no relationship. Though the latency results accord with expectations, the discrepancy between studies on amplitude effects is difficult to account for.

An interesting study by Winkler and Naatanen (1993) suggested that another ERP component, the MMN, might be implicated in differential ability to perform well in auditory discrimination tasks.

Mismatch Negativity

Among the negative endogenous components, the MMN (Naatanen, Gaillard, & Mantysalo, 1978) has been the most extensively studied. MMN is a difference wave derived by subtracting the waveform generated by the standard tones from the waveform elicited by the deviants (the waveform to the deviants is termed N2a). MMN has a modal latency of between 50 and 200 ms. MMN has been posited as an automatic deviance-detector mechanism and in this sense is regarded as a triggering event for the orienting response (Snyder & Hilliard, 1976;

Naatanen et al., 1978). Winkler et al. (Winkler, Paavilainen, Alho, Reinikainen, Sams, & Naatanen, 1990) refer to it as a "biologically vital warning mechanism" (p.228). Escera and Grau (1996) demonstrated the high short-term replicability of MMN latency and amplitude at the group level. At the individual level, however, replicability of latency and amplitude is somewhat less consistent (Escera & Grau, 1996; Pekkonen, Rinne, & Naatanen, 1995), though this may have been a function of too few deviant tones in their study. It should be noted that component identification in terms of latency varies somewhat from laboratory to laboratory, depending on the researcher's area of interest. Naatanen et al., for example, consider the MMN to be a long-latency component (Lavikainen, Tiitinen, May, & Naatanen, 1997).

MMN differs from other endogenous components in that it can be elicited by stimuli that are entirely predictable (Scherg, Vajsar, & Picton, 1989). Generally, endogenous ERP components are relatively small or even absent when stimuli are predictable (Sutton, Braren, Zubin, & John, 1965). As probability of occurrence increases, for example, P3 amplitude decreases. MMN appears to be relatively insensitive to the predictability of the deviant stimulus (Ritter and Ruchkin, 1992), although decreasing the probability of the deviant stimulus (by increasing the probability of the standard stimulus) decreases the strength of the memory trace to the standard stimulus.

The MMN is believed to originate bilaterally in generators localized in the primary auditory cortex (Hari, Hamalainen, Ilmoniemi, Kaukoranta, Reinikanen, Salminen, Alho, Naatanen, & Sams, 1984), and also in the right frontal lobe (Giard, Perrin, Pernier, & Bouchet, 1990). (It should be noted that component identification in terms of latency varies somewhat from laboratory to laboratory, depending on the researcher's area of interest. Naatanen et al., for example. consider the MMN to be a long-latency component (Lavikainen. Tiitinen. May. & Naatanen. 1997).

Another important difference between MMN and other endogenous components is that it can be elicited in the absence of awareness or attention. In the absence of attention. a deviant stimulus occurring randomly within a series of tones elicits the MMN (or rather the N2a. from which the MMN is subsequently derived). When the subject is engaged in some unrelated task. for example. reading a book. he or she is typically unaware that deviant tones were present when questioned afterwards.

The functional significance of the MMN lies in its indexing the contents of the auditory buffer. also known as echoic memory (Cowan. 1984; Neisser. 1967). Massaro (1970. 1971) used backward recognition masking. or simply backward masking to delineate the chronometry of echoic memory. Winkler et al. (Winkler. Tervaniemi. Huotilainen. Ilmoniemi. Ahonen. Salonen. Standertskjold-Nordenstam. & Naatanen. 1995) note that "since the advent of the information-processing models of human cognition. auditory sensory memory. also called echoic memory. has been regarded as a temporary store of raw sensory data. a more or less exact replica of the external sensory event" (p.2317). Latency to peak amplitude indicates the amount of time required to complete the sensory discrimination process. Peak amplitude indexes the "strength of the memory trace" (Winkler et al.. 1993. p.448). As previously mentioned. larger amplitudes translate to the synchronized activity of the neurons involved in MMN generation. the activity of a larger number of neurons. or both (Hernandez-Collados. 1995); in general. larger amplitudes are concomitant with more information in the echoic buffer. This in turn enhances the individual's ability to perform the active discrimination. As the SOA becomes briefer. or. in

Winkler's terminology, as the effects of masking become stronger, MMN is successively attenuated until the deviant no longer elicits a MMN.

Their test paradigm, designed to further explicate the nature of the auditory buffer, employed the standard auditory oddball procedure but added a backward masking stimulus at SOAs of 20, 50, 150, 300, and 400 ms. The standard (85% probability of occurrence) and deviant tones were 600 and 700 Hz respectively, and both were 25 msec duration. The mask was 1000 Hz and had a duration of 55 msec. In an attend condition (wherein ERPs were not recorded), participants were required to detect the occurrence of the deviant tone. In an ignore condition where participants read a book, the MMN was recorded. Though 10 participants were employed initially, 5 were excluded from the analysis because they were able to perform with almost perfect accuracy even at the shortest SOAs. Behavioural performance data from the 5 remaining individuals was compared with MMN amplitude. Performance accuracy dropped off precipitously for these participants as the SOA was reduced from the 150 msec to the 50 msec SOA. These data are summarized below.

	SOA				
	20	50	150	300	400
MMN amplitude (μv)	-0.63	0.16	-1.76	-1.5	-2.28
Accuracy (% hits)	25.3	12.6	63.2	74.7	85.7

Noting the "very good" correspondence between MMN amplitude and behavioural performance, they point out that both are virtually eliminated by the backward mask occurring at short SOAs. These results, of course, beg the question of why half of their sample could perform the task even at short SOAs and why MMN amplitude was not significantly attenuated at the shorter SOAs, as occurred with the no-ceiling effect group. The data for the "ceiling effect" subjects are summarized in the table below.

	SOA				
	20	50	150	300	400
MMN amplitude (µv)	-0.57	-0.70	-0.88	-0.61	-0.90
Accuracy (% hits)	97.4	95.8	88.4	95.8	96.3

Winkler et al. (1993) make no attempt at interpreting the superior performance of these individuals. Nor is the issue of why superior performance, associated with larger MMN amplitude in the no-ceiling effect group, is concordant with substantially *smaller* MMN amplitude for the ceiling effect group. Given the substantial literature relating intelligence and performance in auditory discrimination tasks, the concordance between MMN amplitude and the percentage of deviants correctly detected, when compared across both groups, are highly suggestive of individual differences in cognitive ability.

The findings from this study, even with the small sample size, are provocative. The paradigm bears remarkable similarities to the Raz paradigm (1983, 1985) described earlier, particularly with the use of decreasing SOAs following a single tone (rather than a constant ISI and decreasing stimulus durations, as in the auditory IT task). That it is based on the auditory oddball is also significant. The oddball paradigm has demonstrated its utility by producing consistent results linking intelligence and performance (Ladish & Polich, 1989; Polich, Ehler, Otis, Mandrell, & Bloom, 1986; Polich, Howard, & Starr, 1985; Polich & Martin, 1992). In addition, it is widely used in ERP studies.

Summary

The literature review has provided evidence that although there are various definitions of intelligence, a predominant theory relates to SIP. Moreover, three general methods of assessing SIP have demonstrated concordance across a wide range of experimental paradigms: RT, IT, and endogenous ERPs. At the most elementary level, it has been shown that shorter RTs, briefer IT thresholds, and shorter latency P3 ERPs are characteristic of individuals of higher intelligence. The ERP research, which informs the present studies, can be summarized as follows.

A robust literature links SIP with individual differences in cognitive ability. Research employing ERPs, collected during the performance of simple discrimination tasks, has shown some promise in elucidating the relation between intelligence and stages of information processing. Intelligence is assessed independently then correlated with ERP data collected during the performance of ECTs.

Overall, RT shows the most consistent (inverse) association with intelligence across a wide variety of ECTs. Studies employing both RT and P3 have extended knowledge of the relation between SIP and cognitive ability. P3 latency indexes the speed of stimulus classification and decision-making processes. In particular, it has been demonstrated that a negative correlation exists between P3 latency and psychometric intelligence. IT studies, too, purport to examine the stage or stages of information processing that are responsible for or mediate the relations between intelligence and performance. Though theoretical and methodological issues are unresolved, IT studies also suggest a speed of information processing component in intelligence.

Inspection time studies using ERPs, though characterized by poor methodologies, attempt to extend behavioural IT studies. The contention that IT - ERP studies allow the examination of operation of sensory processes is doubtful on both theoretical and methodological grounds and is not supported by the cognitive psychophysiology literature. The mismatch negativity, however, is widely held to index the operation of a sensory memory register termed the echoic buffer. Winkler and Naatanen (1993) reported high concordance between MMN amplitude and behavioural performance in a backward-masked auditory oddball paradigm. Moreover, speed of information uptake in the echoic buffer is indexed by the latency of the MMN: the results of their experiment suggest that characteristics of the echoic buffer might mediate differential performance in auditory discrimination tasks.

Purpose of the Present Study

A new paradigm, the backward masked auditory oddball procedure (Winkler and Naatanen, 1993), was applied to the study of intelligence. Attentive change detection was indexed by P3 and by behavioural performance in the attend condition. Automatic change detection was indexed by the MMN in the ignore condition. The present study was conducted to determine what insight this new task can shed on behavioural performance, P3, and MMN, as each relates to intelligence. A secondary goal was to elucidate the relation between speed of information processing at the level of the sensory apparatus and speed of processing in STM.

Hypotheses

It is anticipated that HA participants will exhibit superior performance as characterized by more accurate detection of deviants, fewer false positives, faster processing, as indexed by RT, and smaller intra-individual differences in responding across trials (SDrt). It is also expected that physiological indices, specifically P3 and MMN latencies, will bear some relation to these measures, with shorter latencies observed for the HA groups for both ERP components. Expectations regarding group differences in amplitude are indeterminate for P3 for both MMN and P3.

EXPERIMENT 1

Method

Participants

Thirty-six right-handed. English-speaking females were recruited from introductory psychology classes (mean age = 20.1 years. SD = 3.1 years). Participants were asked to consume no caffeine or alcohol for 24 hours prior to the ERP data collection. All participants were non-smokers. Participants were tested for normal hearing (15 dB ISO) at 500. 1000. 1500. and 2000 Hz using a Lafayette Instrument model 10D audiometer. Participants were screened for the ingestion of psychoactive substances and reported no head injuries. Participants received $10.00 after completing the experiment.

Procedure

In the first session participants completed 2 mental ability tests. the Multidimensional Aptitude Battery (MAB: Jackson. 1984) and der Zahlen-Verbindungs Test (ZVT: Oswald & Roth. 1978). Participants also completed the Eysenck Personality Questionnaire – Revised (EPQ-R: Eysenck & Eysenck. 1985). For the analysis of group differences. participants were selected to form 2 mental ability groups on the basis of the median split of MAB full-scale (FIQ) scores (MD = 113). Individuals in the higher-ability (HA: N = 18) group had FIQ scores ≥ 114: the lower-ability (LA: N = 18) group had FIQ scores ≤ 112. Participants returned within 5 days to complete an auditory discrimination task. A 1-way analysis of variance (ANOVA) indicated that HA and LA groups differed significantly on FIQ ($F(1,34) = 67.8$; $p<.001$). Psychophysiological data were recorded concurrently with behavioural performance on the discrimination task.

Mental Ability Measures

Three increasingly complex versions of the ZVT, a trail-making test that assesses speed of information processing (SIP), were administered (Oswald & Roth, 1978; Vernon, 1993). More complex versions have higher concordance with scores on the MAB (Vernon, 1993), with the most complex version accounting for approximately 50% of the variance in FIQ. In the original version (Oswald & Roth, 1978), the individual is required to connect as many circles, numbered from 1 to 90, as possible within 45 seconds. The score is the highest number reached. This version is here designated $1\text{-}2\text{-}3_{45}$. Vernon (1993) modified the original version in several ways. In one version, circles were now numbered 179 – 177 – 175, and so on, requiring the participant to count backwards by twos; the score is determined by counting the number of correctly connected circles. This version is referred to as $179\text{-}177_{45}$. In the final, most difficult version, the participants much match numbers and letters; the sequence is Z – 26 – Y – 25 – X – 24, and so on ($Z26\text{-}Y25_{45}$). Again, the score is determined by counting the number of correctly connected circles. In addition to completing as much of the form as possible within 45 seconds, participants were also required to complete each version in its entirety. Now total time to completion was recorded. The respective versions in this format are $1\text{-}2\text{-}3_{all}$, $179\text{-}177_{all}$, and $Z26\text{-}Y25_{all}$, respectively.

After a brief break, participants completed the MAB (Jackson, 1984), a well-known, group-administered mental abilities test modeled on the Weschler Adult Intelligence Scale – Revised (WAIS-R; Weschler, 1981). The MAB yields 3 scores: verbal IQ (VIQ), performance IQ (PIQ), and FIQ. The VIQ subscales are Information, Arithmetic, Comprehension, Vocabulary, and Similarities. The PIQ subscales are Digit Symbol, Picture Completion, Spatial, Picture Arrangement, and Object Assembly.

Participants also indicated overall grade for the previous academic year on a 5-point Likert scale (<60%, 61-70%, 71-80%, 81-90%, 91-100%).

Personality Measures

Finally, subjects completed the EPQ-R (Eysenck & Eysenck, 1985), a 106 item instrument that assesses 3 measures of personality: Psychoticism (P), Extraversion (E), and Neuroticism (N). The EPQ-R also has a Lie scale that assesses dissimulation.

Behavioural and Physiological Measures

1) Auditory Discrimination Task

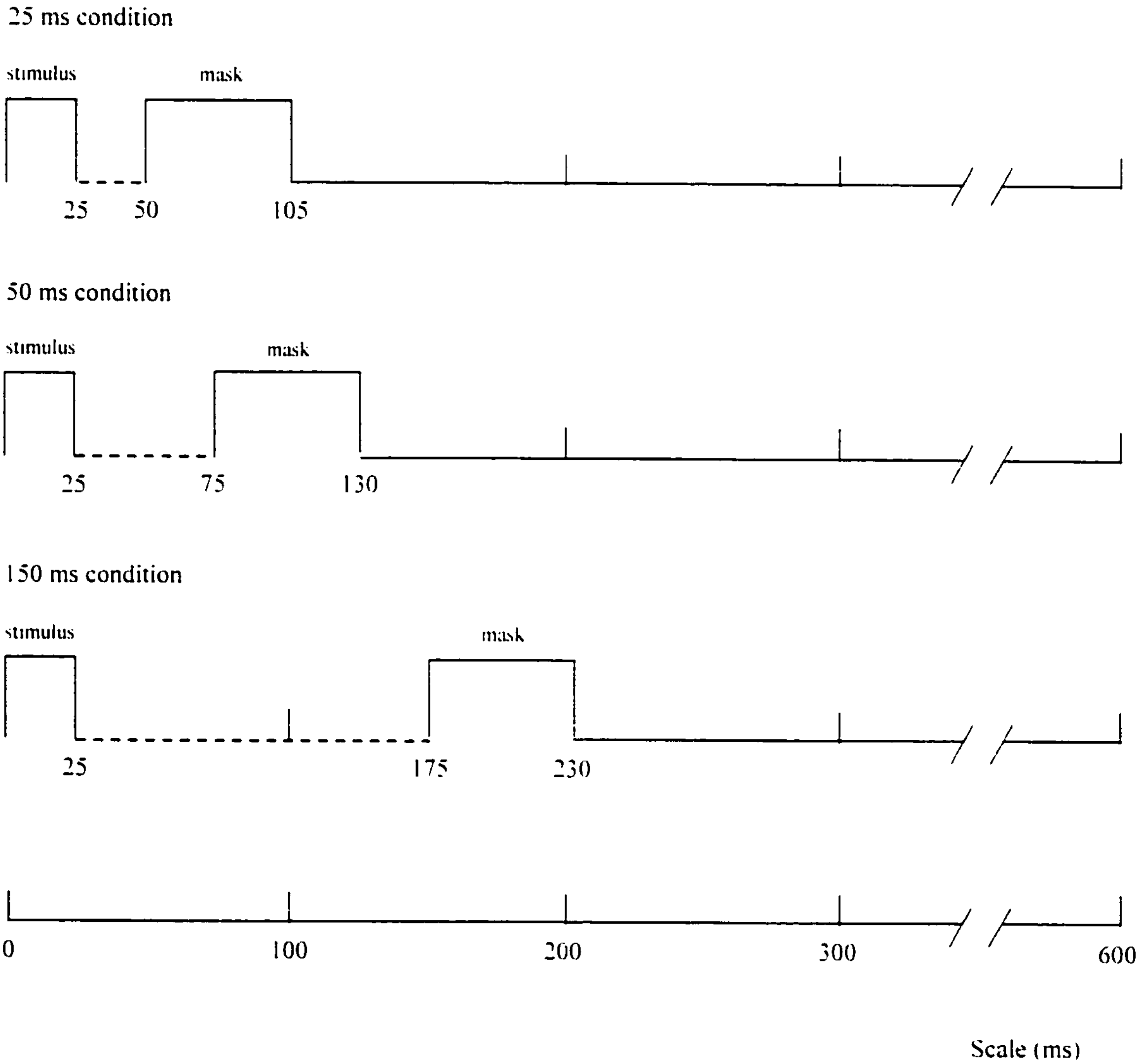
Participants were seated about 40 cm in front of a computer monitor in an acoustically shielded room. The auditory discrimination task consisted of the presentation of a series of frequently occurring standard tones, presented in 85% of trials, and infrequently occurring deviant tones, presented in 15% of trials. For each trial, the standard and deviant tones were followed by a masking tone that controlled the duration of exposure of these tones. The tones were presented binaurally through headphones.

The standard tones had a frequency of 600 Hz. The deviant tones had a frequency of 700 Hz. The masking tone had a frequency of 1000 Hz. All of the tones had an intensity of 88 dB SPL, as determined by a Bruel and Kjaer model 1613 sound level meter, and a rise and fall time of 2.5 ms. The duration of the standard and deviant tones was 25 ms. The duration of the masking tone was 55 ms.

The interval between the offset of the standard or deviant tone and the onset of the masking tone, the SOA, was varied at 25, 50 and 150 ms. For each of the SOA conditions, the inter-trial interval was 600 ms. The timing sequence of the auditory discrimination task is depicted in Figure 3. SOAs are indicated by dashed lines. (Note that the figure does not include the 60 ms pre-stimulus baseline.)

Figure 3

Timing Sequence for Backward-masked Auditory Discrimination Task



Each of the three SOA conditions was comprised of two blocks of 500 trials. 425 standard tones and 75 deviant tones, presented in a random order. The order of presentation of the 6 blocks of trials was also presented in a random order. This presentation procedure was administered to each subject under two conditions, an ignore condition in which the participant was instructed to ignore the tones and to read a book and an attend condition in which the participant was instructed to detect the occurrence of the deviant tone.

The ignore condition was administered to each subject before they were administered the attend response condition. Participants were not informed prior to the presentation of the trials in the ignore condition that the stimulus series consisted of standard and deviant tones that differed in frequency. When they were questioned on this at the end of the procedure, none of the participants indicated that they were aware of the difference in frequency between the standard and deviant tones during the ignore condition.

In the subsequent administration of the attend response condition, participants were instructed to rest their right index finger on the space bar of the computer keyboard and to press it when they detected a deviant stimulus. They were told to press the space bar as quickly as possible while maintaining accuracy. Participants were given a brief practice session in the easiest discrimination condition, 150 ms SOA, to ensure that they understood the discrimination task. They were required to correctly detect 5 consecutive deviant tones before continuing with the procedure.

2) Electrophysiological Recording

Electroencephalogram (EEG) was recorded from 5 electrode sites (F_Z, C_Z, P_Z, M_1, and M_2; Jasper, 1958). All electrode sites were referenced to the tip of the nose. The ground electrode was located in the electrode cap 10 mm anterior to F_Z. Horizontal EOG was recorded from electrodes placed 1 cm from the outer canthi of each eye. Vertical EOG was recorded from electrodes placed 1 cm above and below the upper and lower canthus of the right eye, respectively. Electro-oculogram (EOG) and data from M_1 and M_2 were recorded using Grass™ Ag-AgCl cup electrodes. Data from all other sites were recorded using an Electro-Cap International™ electrode cap. Inter-electrode impedances were less than 5 kΩ. The EEG and EOG were recorded continuously to hard disk at a sampling rate of 256 Hz.

3) Data Analysis

An offline EOG correction subroutine was employed (Woestenburg, Verbaten, & Slangen, 1983), with artifact rejection set at ± 100 μv. Data were digitally filtered using a bandwidth of 3 to 12 Hz (3 dB roll-off). The EEG was later reconstructed into discrete single trial epochs. An epoch began 60 ms prior to stimulus onset and continued for 940 ms following it. The data after 600 ms is of course difficult to interpret because the waveform is composed of a summation of the effects of the target and the onset of the subsequent stimulus.

Trials for each block of the ignore condition were classified by a computerized averaging routine (InstEP Systems™) as being to standards or deviants. Averaged ERP waveforms to the standard tones were subtracted from averaged waveforms to the deviant tones. The resulting difference wave, measured at the Fz electrode site, is the MMN.

Trials in each block of the attend condition were also classified as being to standards or deviants. Trials were further classified as being 1) correct non-response to standards; 2) incorrect response to standards (false positives); 3) correct response to deviants (hits); and 4) incorrect non-response to deviants (misses). Averaged ERP waveforms to 1) and 3) were compared. Correct responses to deviants elicited P3, which was measured at Pz.

A computer-assisted scoring (CAS) routine (InstEP Systems™) was used to score all waveforms for amplitude and latency. For P3, measured at Pz, the period was 280-440 ms. For the MMN, the CAS routine was set to detect peak amplitude at the Fz electrode site within a 100-240 ms period after standard or deviant onset. Waveforms components were visually inspected to corroborate the accuracy of the CAS program.

4) Statistical Analysis

Ability-group by SOA repeated measures analyses of variance (ANOVA) with Geisser-Greenhouse epsilon adjustments were performed to determine whether group membership or SOA (or an interaction between the two) had an effect on the dependent variables. Tukey's honestly-significant-difference (HSD) tests were used for all post hoc analyses. ANOVA results are reported only when p values are < .05. All correlational analyses used Pearson product-moment correlations.

Results

Means and standard deviations for all dependent variables are shown in Tables 1 to 3. Correlations between FIQ and all variables are shown in Table 4. Grand average waveforms for HA and LA ability groups for each SOA are shown in Figures 4 and 5 for attend and ignore conditions, respectively. Bar charts for accuracy, reaction time and P3 latency, and P3 amplitude are shown in Figures 6, 7, and 8, respectively.

Performance Measures

Experimental Effect

There was no effect of SOA on percent correct responses or number of false positives. Duration of the SOA influenced RT to correct responses ($F(4,95)=4.04$; $p<.05$), with longer RTs in the 150 ms SOA condition (428.0 ms) than in the 50 (405.4 ms) or 25 ms SOA (409.8 ms) conditions. SOA also influenced SDrt ($F(2,68)=4.30$; $p<.05$). Standard deviation of mean reaction time was larger at the 150 and 25 ms SOAs than at the 50 ms SOA. SOA had no effect on false positives.

Group Membership

Higher ability participants detected significantly more deviant tones than individuals in the LA group ($F(1,34)=7.80$; $p<.01$). Post-hoc tests indicated that group differences in accuracy were only significant at the 150 ms SOA, though accuracy approached significance at both the 50 ms ($p=.069$) and 25 ms ($p=.054$) SOAs.

The HA group had faster mean reaction times to correct responses ($F(1,34)=4.95$; $p<.05$) at the 150 and 50 ms SOAs. Standard deviation of mean reaction time for each individual also varied inversely with ability ($F(1,34)=8.83$; $p<.01$), with HA participants showing more consistency in their responses across all SOAs. HA individuals had fewer false positives than LA participants. There was no ability group by SOA interaction for any of the discrimination task performance variables.

ERP Measures

Experimental Effect

Duration of the SOA had no influence on latency or amplitude for either P3 or N2b. Though shorter SOAs elicited faster MMN latencies (193.8, 186.9, and 178.4 at 150, 50, and 25 ms SOAs, respectively), the differences were not significant. SOA did not influence MMN amplitude. A phase inversion of MMN was observed at the M1 electrode site.

Group Membership

Group differences in P3 latency were observed ($F(1,34)=5.3$; $p<.05$), though the effect was only significant at 25 ms (HA=364.9 ms, LA=424.6 ms). HA participants exhibited significantly larger P3 amplitude at all SOAs ($F(1,34)=10.3$; $p<.01$). Group differences in N2b latency and amplitude were not significant. There was no interaction between mental ability group and SOA on either P3 or N2b latency or amplitude.

Group differences in both MMN latency and amplitude were not significant. There were no interactions between SOA and group membership on either variable, although a linear increase in group differences in MMN latency were observed with decreasing SOA (6.7, 10.3, and 15.9 ms). In addition, the largest difference in MMN amplitude (1.12 uv) was observed at 25 ms SOA.

Correlational Analysis

Correlational analyses corroborated ANOVA results (see Table 2) for performance variables, with all correlations in the expected directions. Significant correlations between FIQ and SDrt were observed at all SOAs (-.56, -.47, and -.35 for decreasing SOAs). Correlational analyses for attend ERP measures were also consistent with ANOVAs. Correlations between FIQ and P3 amplitude were .38, .43, and .35 (all significant at $p<.05$) for 150, 50, and 25 ms SOAs, respectively. A significant correlation was observed between FIQ and P3 latency ($r=-.51$, $p<.01$) at the 50 ms SOA. MMN amplitude at the 25 ms SOA also correlated with FIQ ($r=-.50$, $p<.01$) only.

Table 1

Means (SDs) for Discrimination Task Behavioural Performance Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=36)

	Correct Detections (%)		
	150	50	25
HA	92.0 (8.2)	90.5 (11.4)	88.8 (12.4)
LA	81.9 (13.4)	83.4 (11.5)	80.9 (11.2)
N=36	87.0 (12.1)	86.9 (11.9)	84.9 (12.3)
	False Positives		
	150	50	25
HA	1.7 (2.3)	2.2 (3.4)	2.3 (3.1)
LA	4.1 (5.3)	3.9 (6.2)	5.7 (7.8)
N=36	2.9 (4.2)	3.1 (5.0)	4.0 (6.1)
	RT (ms)		
	150	50	25
HA	384.6 (91.4)	372.0 (95.9)	381.8 (121.8)
LA	471.4 (94.8)	438.8 (82.0)	437.9 (101.7)
N=36	428.0 (101.8)	405.4 (94.2)	409.8 (114.2)
	SDrt (ms)		
	150	50	25
HA	108.9 (46.6)	101.6 (32.2)	112.7 (56.4)
LA	174.3 (70.1)	144.8 (49.4)	164.5 (83.6)
N=36	141.6 (67.4)	123.2 (46.6)	138.6 (75.0)

Table 2

Means (SDs) for P3 and N2b ERP Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=36)

	P3 Latency (ms)		
	150	50	25
HA	385.5 (78.8)	376.4 (62.5)	364.9 (69.3)
LA	418.5 (79.6)	403.8 (71.2)	424.6 (72.8)
N=36	402.0 (79.8)	390.1 (67.5)	394.7 (76.3)
	P3 Amplitude (μv)		
	150	50	25
HA	14.8 (5.7)	15.4 (7.4)	15.7 (9.6)
LA	9.2 (5.5)	9.0 (5.7)	8.8 (4.6)
N=36	12.0 (6.2)	12.2 (7.3)	12.3 (8.2)
	N2b Latency (ms)		
	150	50	25
HA	223.6 (39.4)	205.0 (29.0)	221.7 (44.3)
LA	235.8 (53.7)	241.0 (50.8)	225.3 (38.0)
N=36	229.7 (46.8)	223.0 (44.7)	223.5 (40.7)
	N2b Amplitude (μv)		
	150	50	25
HA	5.3 (4.2)	5.1 (3.4)	5.1 (5.6)
LA	5.6 (3.9)	5.6 (3.9)	5.2 (3.2)
N=36	5.5 (4.0)	5.3 (3.6)	5.1 (4.5)

Table 3

Means (SDs) for MMN ERP Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=36)

	MMN Latency (ms)		
	150	50	25
HA	190.4 (19.9)	181.7 (27.6)	170.4 (34.0)
LA	197.1 (30.9)	192.0 (42.9)	186.3 (33.0)
N=36	193.8 (25.8)	186.9 (36.0)	178.4 (34.0)
	MMN Amplitude (μv)		
	150	50	25
HA	2.6 (2.8)	1.9 (1.4)	2.6 (2.0)
LA	1.9 (1.9)	1.9 (1.2)	1.5 (2.1)
N=36	2.2 (2.4)	1.9 (1.3)	2.0 (2.1)

Table 4

Correlations between Full-scale IQ and Performance and ERP Measures at 150, 50, and 25 ms SOAs N=36)

	SOA		
	150	50	25
Discrimination Task Measures			
Percent Correct Detections	.40 *	.21	.38 *
False Positives	-.27	-.16	-.25
RT	-.45 **	-.45 *	-.26
SDrt	-.56 **	-.47 **	-.35 *
ERP Measures – Attend			
P3 Latency	-.11	-.26	-.51 **
P3 Amplitude	.38 *	.43 *	.43 *
N2b Latency	-.18	-.23	.02
N2b Amplitude	-.15	-.25	-.16
ERP Measures – Ignore			
MMN Latency	.04	-.28	-.24
MMN Amplitude	-.10	-.24	-.51 **

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

Figure 4

ERP Waveforms and RT Histograms for Ability Groups during the Active Condition, 150, 50, and 25 ms SOAs (N=36)

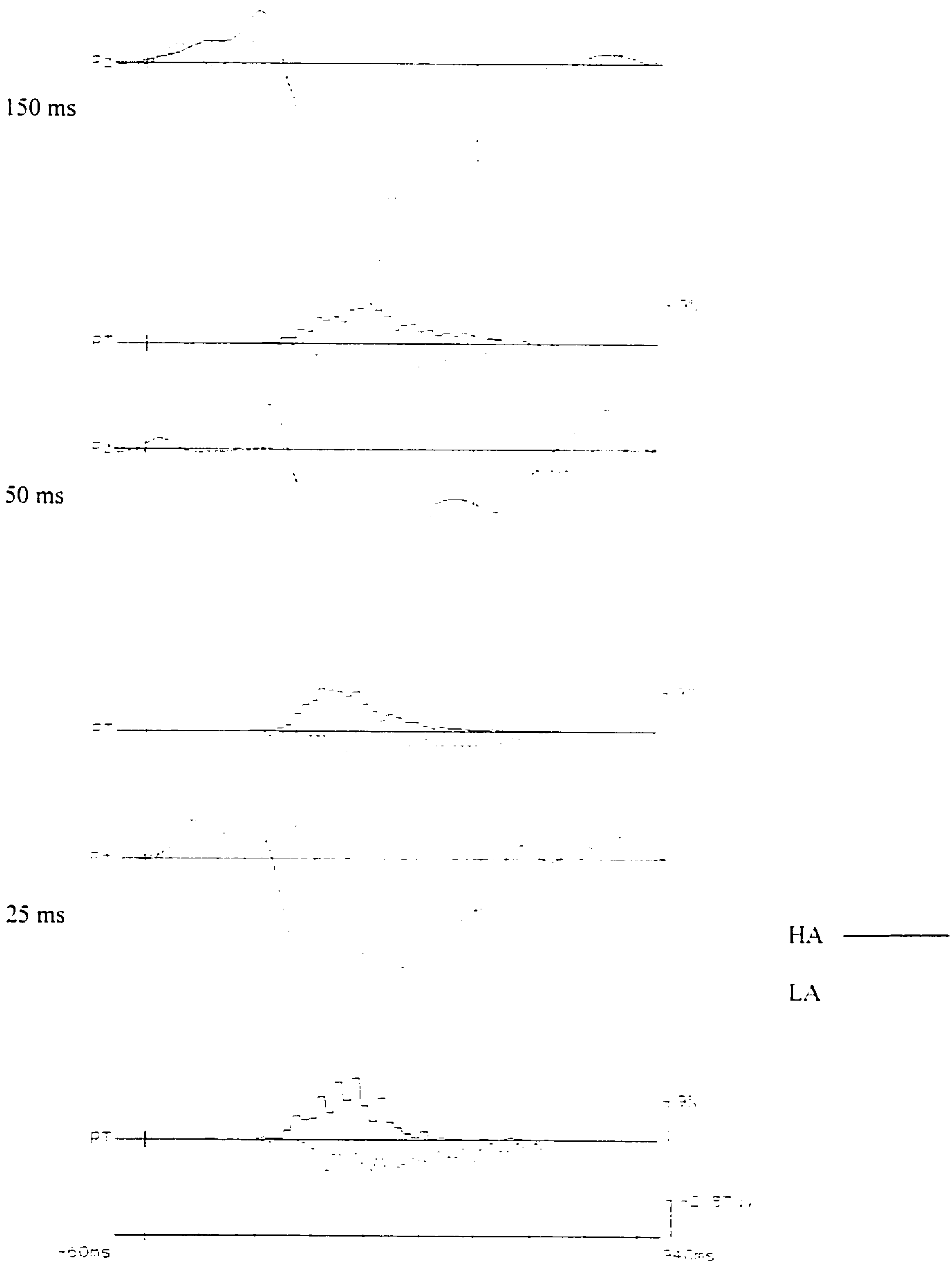


Figure 5

ERP Waveforms for Ability Groups during the Passive Condition, 150, 50, and 25 ms SOAs (N=36)

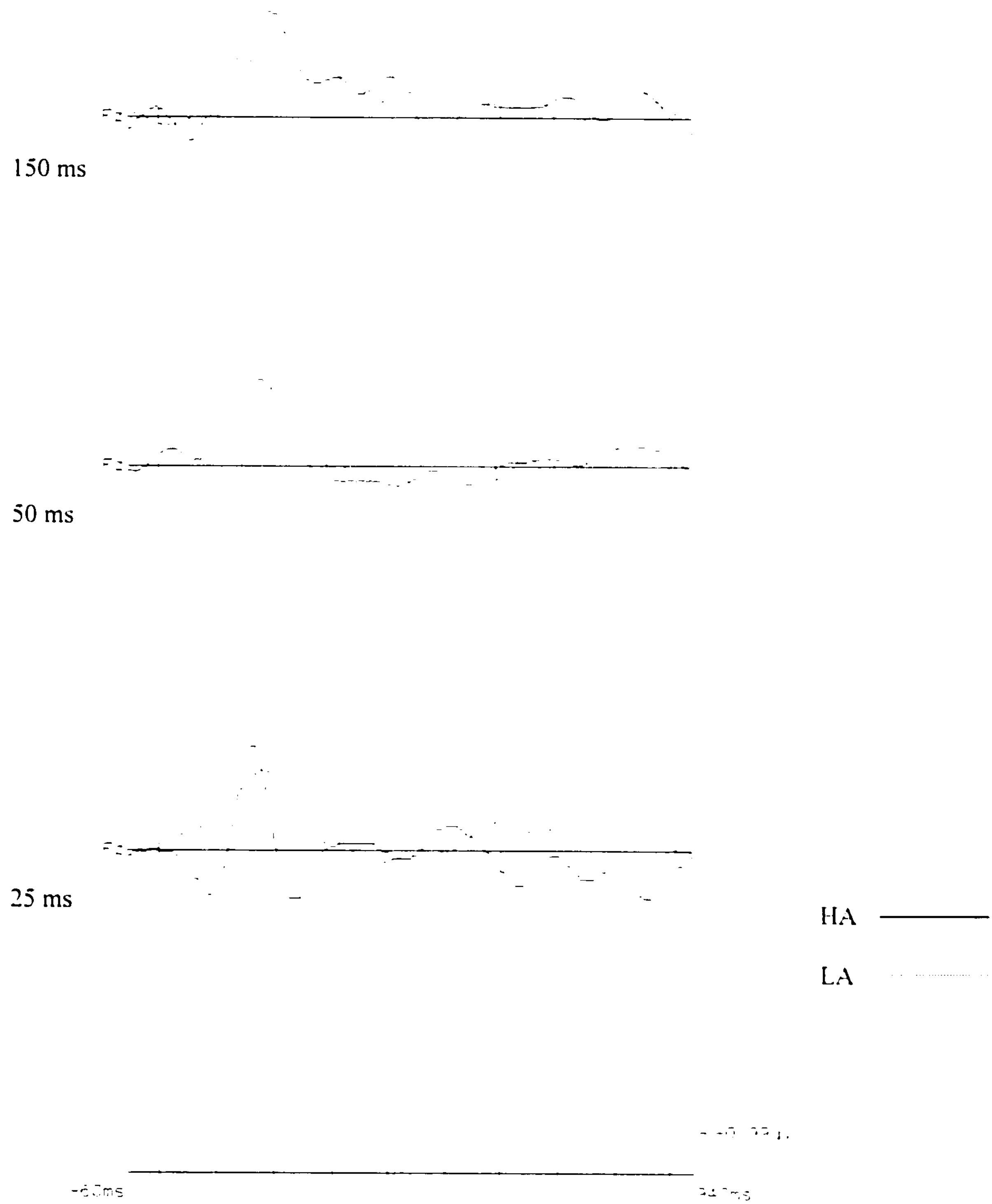


Figure 6

Plot of Means (SEs) for Percent Correct Detections for Ability Groups at 150, 50, and 25 ms SOAs (N=36)

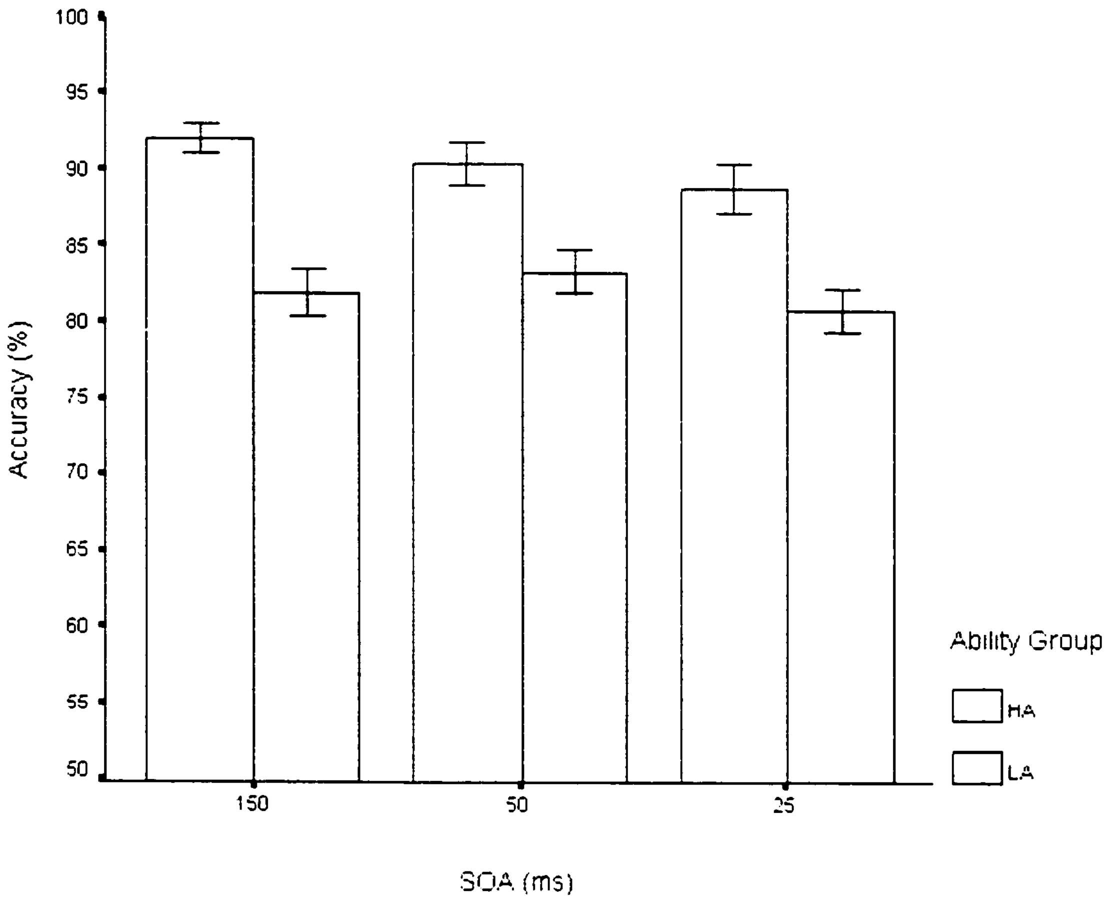


Figure 7

Plot of Means (SEs) for RT and P3 Latency for Ability Groups at 150, 50, and 25 ms SOAs (N=36)

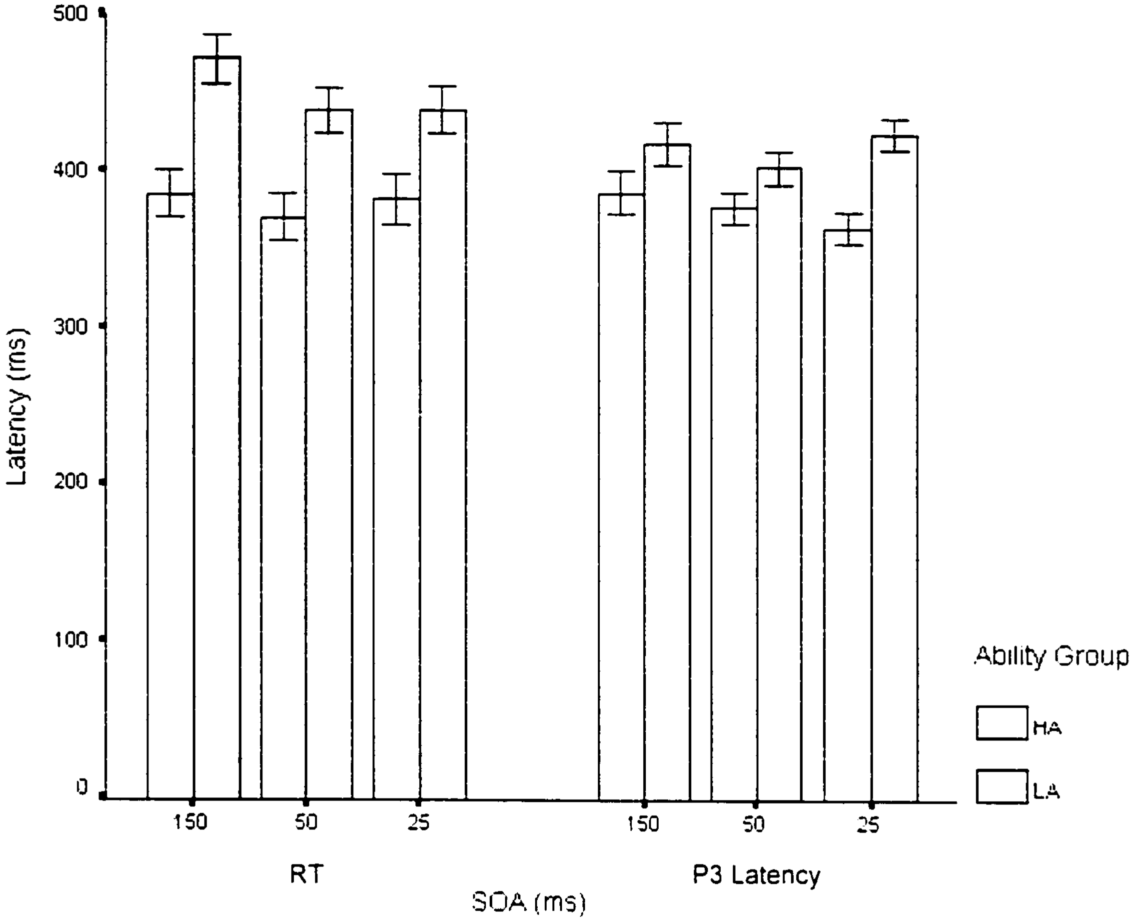
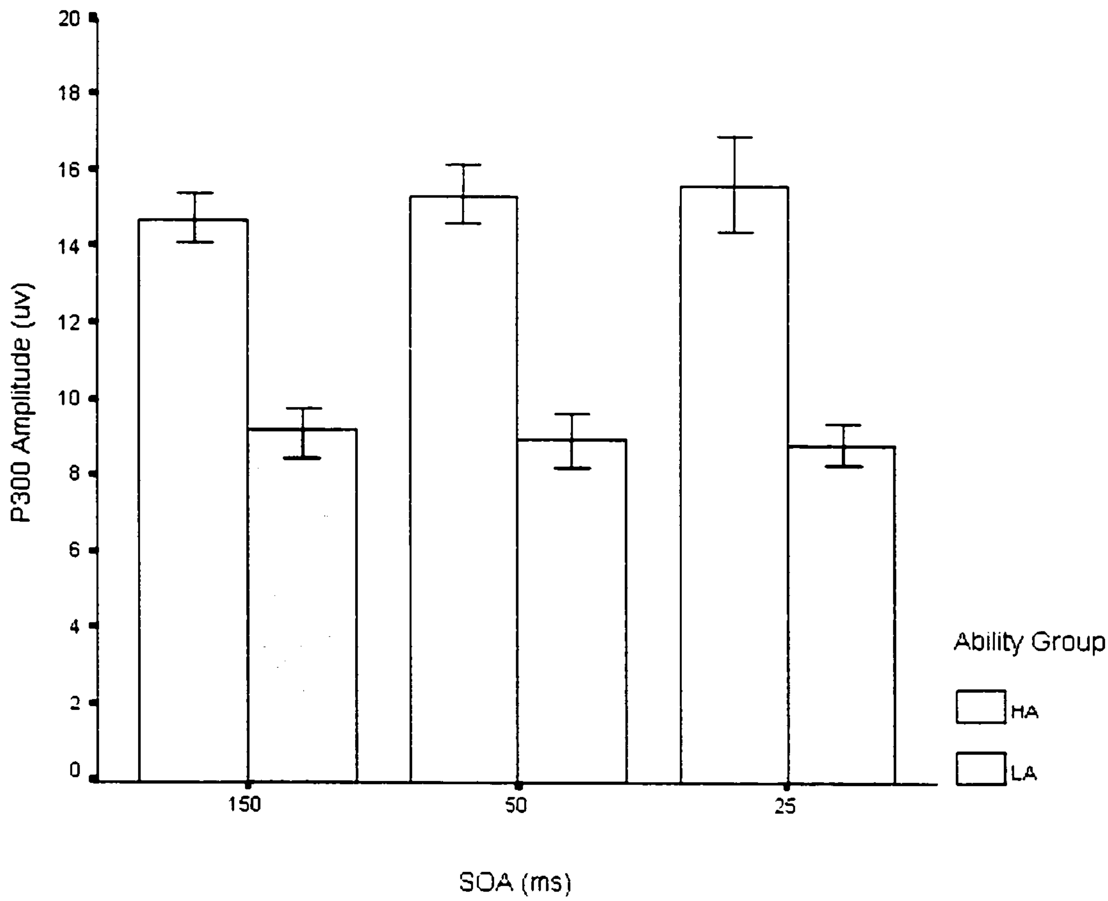


Figure 8

Plot of Means (SEs) for P3 Amplitude for Ability Groups at 150, 50, and 25 ms SOAs (N=36)



EXPERIMENT 2

Method

Participants

Twenty-four right-handed, English-speaking females were recruited from introductory psychology classes (mean age = 19.8 years, SD = 3.3 years). Participants were tested for normal hearing and screened as described above. Data on menstrual cycle was collected and time-of-day (in minutes past midnight) was recorded. Participants were paid $10.00 after completing the experiment.

Procedure

Participants were again selected to form 2 mental ability groups on the basis of the median split of MAB FIQ scores (MD = 115). Individuals in the HA group had FIQ scores ≥ 116 (N = 12; mean = 121.1; SD = 5.13); the LA group had FIQ scores ≤ 114 (N = 12; mean = 107.0; SD = 5.97). Participants returned within 5 days to complete the auditory discrimination task. A 1-way analysis of variance (ANOVA) indicated that HA and LA groups differed significantly on FIQ ($F(1,22) = 38.5$, $p<.001$).

Behavioural and Physiological Measures

Ignore and attend sessions were administered in a manner identical to Study 1, with the addition of 2 intensity conditions. Stimuli were now presented at 88 dB, as in study 1, and also at 82 and 76 dB. The two additional intensity conditions were added in order to manipulate task difficulty (it was expected that decreasing intensity levels would result in graded changes in performance, with the most difficult discriminations occurring at 76 dB). Because this tripled the number of conditions, the number of blocks per condition was reduced to one instead of two.

Each of the nine SOA – intensity conditions was comprised of one block of 500 trials. 425 standard tones and 75 deviant tones. presented in a random order. The order of presentation of the 9 blocks of trials was random. This presentation procedure was again administered to each subject under two conditions. an ignore condition in which the participant was instructed to ignore the tones and to read a book and an attend condition in which the participant was instructed to detect the occurrence of the deviant tone.

Results

Data from the 88 dB condition are presented first in order to determine whether the results of Experiment 1 were replicated. Data from the intensity manipulation are then examined.

Replication

Means and standard deviations for all dependent variables are shown in Tables 5 to 7. Correlations between FIQ and all variables are shown in Table 8. Grand average waveforms for HA and LA ability groups for each SOA are shown in Figures 9 and 10 for attend and ignore conditions. respectively. Bar charts for percent correct detections. RT and P3 latency. and P3 amplitude are shown in Figures 11. 12. and 13. respectively.

Performance Measures

Experimental Effect

There was no significant effect of SOA on accuracy. RT. or SDrt. though all values were in the expected directions. Decreasing SOA produced significantly more false positives at 25 and 50 ms than at 150 ms ($F(2.44) = 6.86$: $p<.01$).

Group Membership

HA participants detected significantly more deviant tones than individuals in the LA group ($F(1.22) = 9.30$: $p<.01$) at all SOAs.

The HA group had faster mean reaction times to correct responses. though differences were not significant at any SOA (see Figure 11). Standard deviation of mean reaction time for each individual also varied inversely with ability ($F(1,22) = 5.35$; $p<.05$). with HA participants showing more consistency in their responses at 150 and 25 ms SOAs (see Table 3). Higher ability participants had fewer false positives overall. though the differences were not significant. There was no ability group by SOA interaction for any of the discrimination task performance variables.

ERP Measures

Experimental Effect

Duration of the SOA had no influence on P3 latency or amplitude. The 150 ms SOA produced significantly longer N2b latency than did the 25 ms SOA. SOA had no effect on N2b amplitude. The 150 ms SOA elicited a briefer MMN latency at 25 ms as compared with 150 ms ($F(2,44) = 5.25$; $p<.01$). SOA did not influence MMN amplitude. A phase inversion of MMN was observed at the M1 electrode site.

Group Membership

No group differences in P3 latency were observed. though the trend was in the expected direction. HA participants exhibited larger P3 amplitude 50 and 25 ms SOAs ($F(1,22) = 5.19$; $p<.05$). There was no interaction between mental ability group and SOA on either P3 latency or amplitude.

Group differences in N2b latency were not significant. nor were there group differences in N2b amplitude. No interaction between SOA and group was observed for N2b amplitude.

Significant group differences in MMN latency were observed at the 25 ms SOA ($F(1,22) = 13.45$; $p<.01$), though differences in MMN amplitude were not apparent. There were no interactions between SOA and group membership on either variables.

Correlational Analysis

Correlational analyses corroborated ANOVA results for performance variables, with all correlations in the expected directions. Here, however, significant correlations between FIQ and reaction time were observed at the 150 ms and 50 ms SOAs ($r = -.44$, and $-.45$, respectively, both significant at $p<.05$). Significant correlations between FIQ and SDrt were observed at 150 and 25 ms, as the ANOVA revealed. Correlational analyses for attend ERP measures were also consistent with ANOVAs, with correlations between FIQ and P3 amplitude of .41 and .46 (both significant at $p<.05$) at 50 and 25 ms SOAs, respectively. In contrast with Experiment 1, where a significant correlation was observed between FIQ and MMN amplitude, here concordance was observed between FIQ and MMN latency at the 25 ms SOA ($r = -.50$, $p<.05$).

Table 5

Means (SDs) for Discrimination Task Behavioural Performance Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=24)

	Correct Detections (%)		
	150	50	25
HA	89.6 (9.7)	87.2 (7.8)	88.8 (10.4)
LA	81.2 (9.5)	80.1 (12.3)	77.4 (12.1)
N=24	85.4 (10.3)	83.6 (10.7)	83.1 (12.5)
	False Positives		
	150	50	25
HA	1.8 (1.4)	6.0 (5.5)	10.1 (9.7)
LA	4.9 (4.8)	9.4 (11.9)	12.2 (12.1)
N=24	3.4 (3.8)	7.7 (9.3)	11.1 (10.8)
	RT (ms)		
	150	50	25
HA	413.4 (71.7)	382.4 (91.6)	383.6 (92.8)
LA	455.1 (75.0)	434.8 (98.1)	417.2 (95.1)
N=24	434.2 (74.9)	408.6 (96.6)	400.4 (93.5)
	SDrt (ms)		
	150	50	25
HA	118.3 (45.7)	110.0 (58.5)	86.6 (37.6)
LA	155.7 (34.5)	148.0 (93.2)	149.9 (84.0)
N=24	137.0 (43.9)	129.0 (78.5)	118.2 (71.4)

Table 6

Means (SDs) for P3 and N2b ERP Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=24)

	P3 Latency (ms)		
	150	50	25
HA	423.1 (44.3)	391.5 (45.1)	384.7 (59.3)
LA	425.0 (49.1)	404.5 (55.1)	414.2 (50.3)
N=24	424.1 (45.8)	398.0 (49.7)	399.4 (55.9)
	P3 Amplitude (μv)		
	150	50	25
HA	12.9 (8.4)	13.5 (8.4)	14.1 (8.3)
LA	8.4 (4.7)	7.1 (4.7)	6.9 (6.3)
N=24	10.6 (7.0)	10.3 (7.4)	10.5 (8.1)
	N2b Latency (ms)		
	150	50	25
HA	243.3 (44.8)	239.0 (34.8)	215.3 (38.1)
LA	233.2 (22.0)	211.3 (30.0)	211.7 (30.2)
N=24	238.3 (34.9)	225.2 (34.8)	213.4 (33.7)
	N2b Amplitude (μv)		
	150	50	25
HA	4.7 (4.3)	4.3 (4.6)	3.2 (6.7)
LA	5.5 (4.3)	5.6 (4.5)	3.7 (4.7)
N=24	5.1 (4.2)	5.0 (4.5)	3.5 (5.7)

Table 7

Means (SDs) for MMN ERP Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=24)

	MMN Latency (ms)		
	150	50	25
HA	187.4 (48.8)	189.4 (34.5)	144.6 (34.4)
LA	215.4 (19.9)	197.2 (40.9)	184.1 (42.6)
N=24	201.4 (39.2)	193.3 (37.2)	164.4 (42.9)

	MMN Amplitude (µv)		
	150	50	25
HA	1.2 (1.7)	2.4 (2.3)	2.0 (2.8)
LA	2.2 (1.9)	1.9 (2.5)	2.4 (2.8)
N=24	1.7 (1.8)	2.1 (2.3)	2.2 (2.7)

Table 8

Correlations between Full-scale IQ and Performance and ERP Measures at 150, 50, and 25 ms SOAs (N=24)

	SOA		
	150	50	25
Discrimination Task Measures			
Percent Correct Detections	.46 *	.52 *	.53 **
False Positives	-.37	-.04	.03
RT	-.44 *	-.45 *	-.28
SDrt	-.54 **	-.36	-.42
ERP Measures – Attend			
P3 Latency	-.23	-.35	-.33
P3 Amplitude	.32	.41 *	.46 *
N2b Latency	.17	.24	-.04
N2b Amplitude	.08	.11	.01
ERP Measures – Ignore			
MMN Latency	-.37	.06	-.50 *
MMN Amplitude	.18	-.30	-.06

Φιγυρε 13 $p < .05$. ** $p < .01$.

Figure 9

ERP Waveforms and RT Histograms for Ability Groups during the Active Condition, 150, 50, and 25 ms SOAs (N=24)

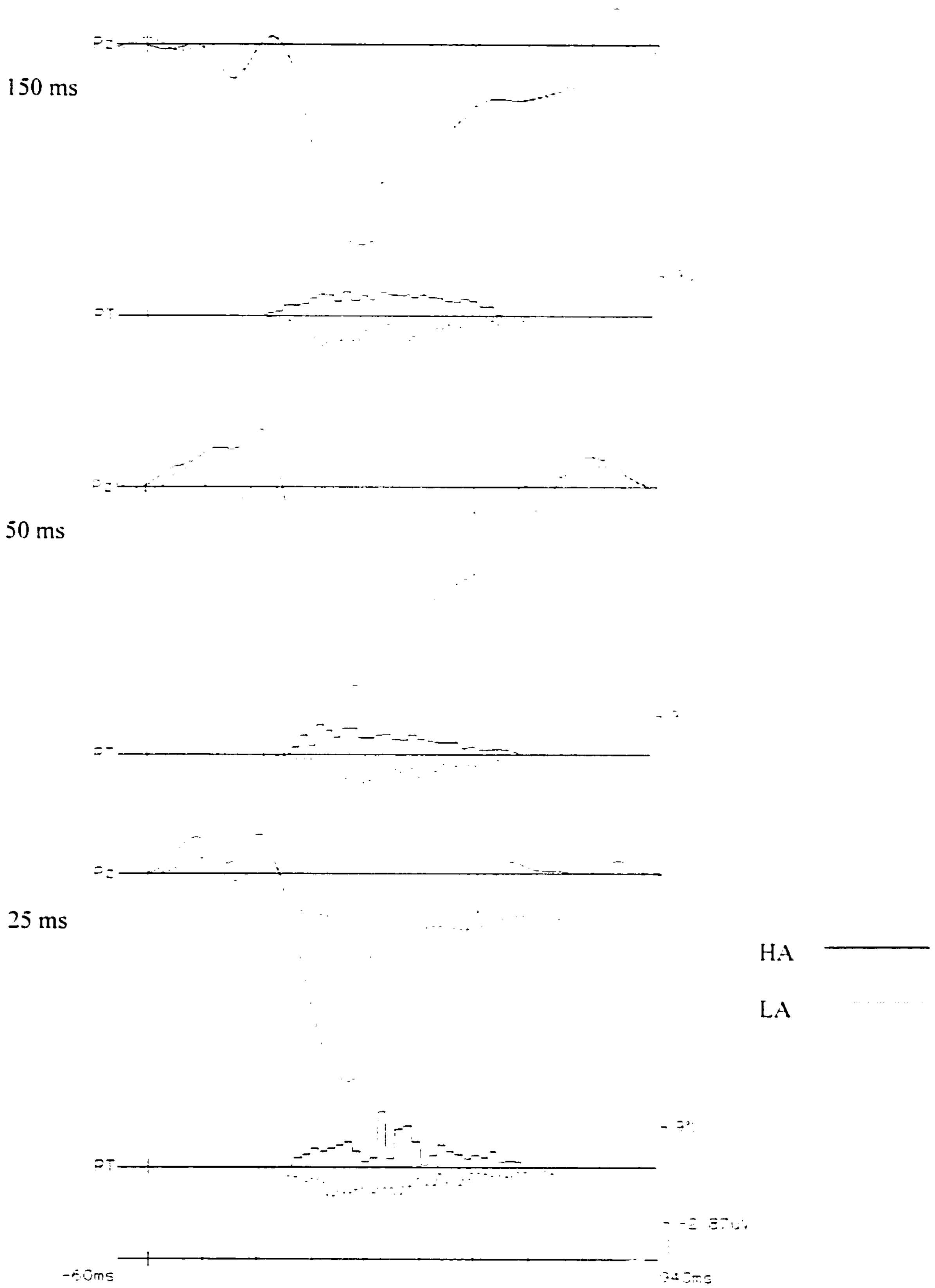


Figure 10

ERP Waveforms for Ability Groups during the Passive Condition, 150, 50, and 25 ms SOAs (N=24)

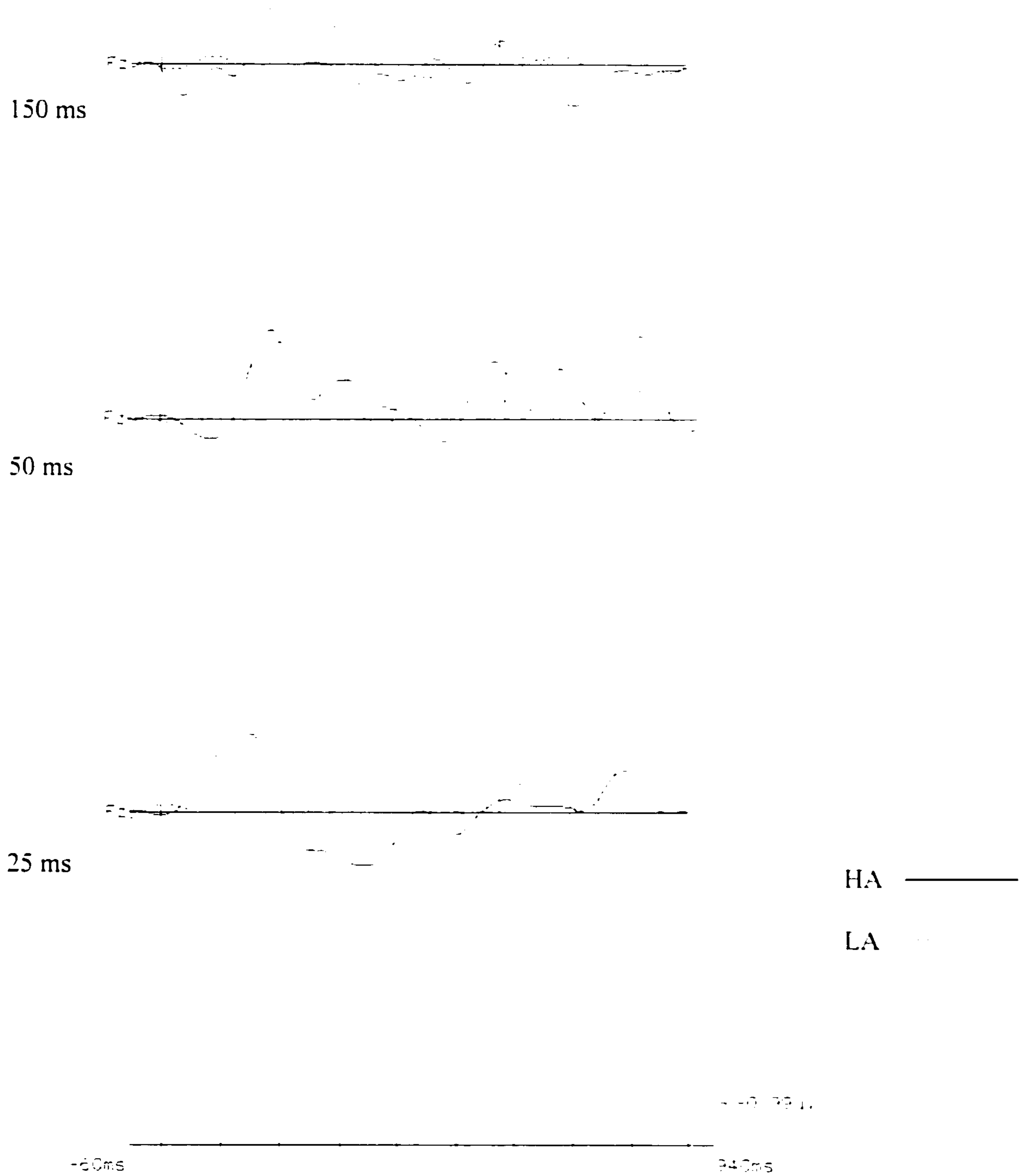


Figure 11

Plot of Means (SEs) for Percent Correct Detections for Ability Groups at 150, 50, and 25 ms SOAs (N=24)

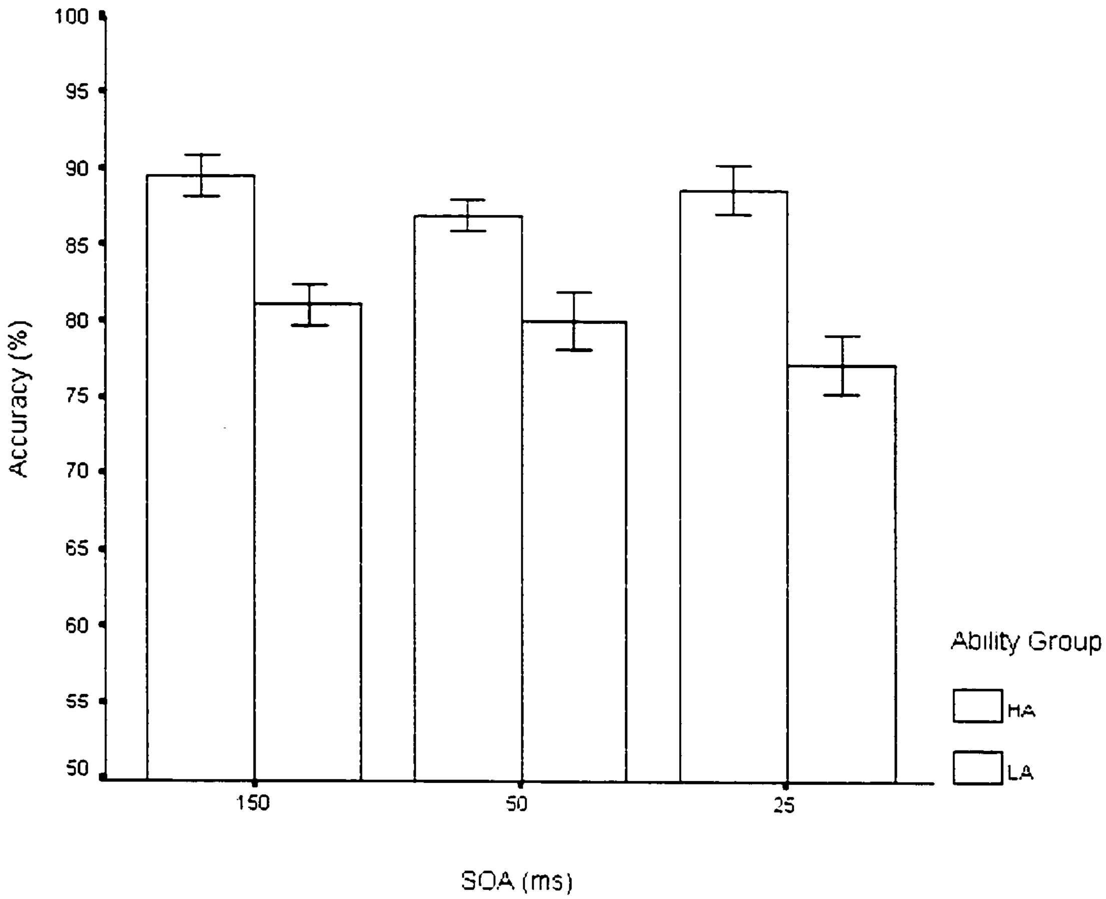


Figure 12

Plot of Means (SEs) for RT and P3 Latency for Ability Groups at 150, 50, and 25 ms SOAs (N=24)

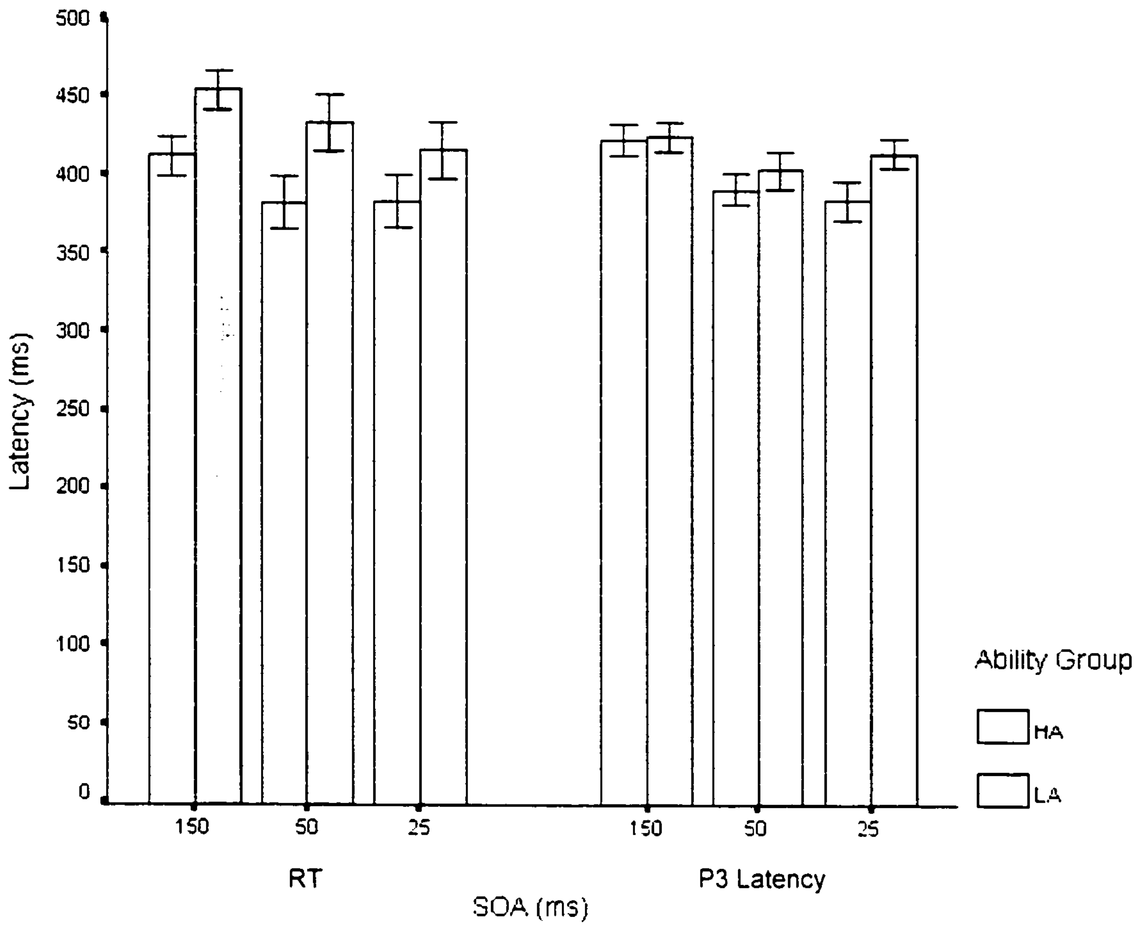
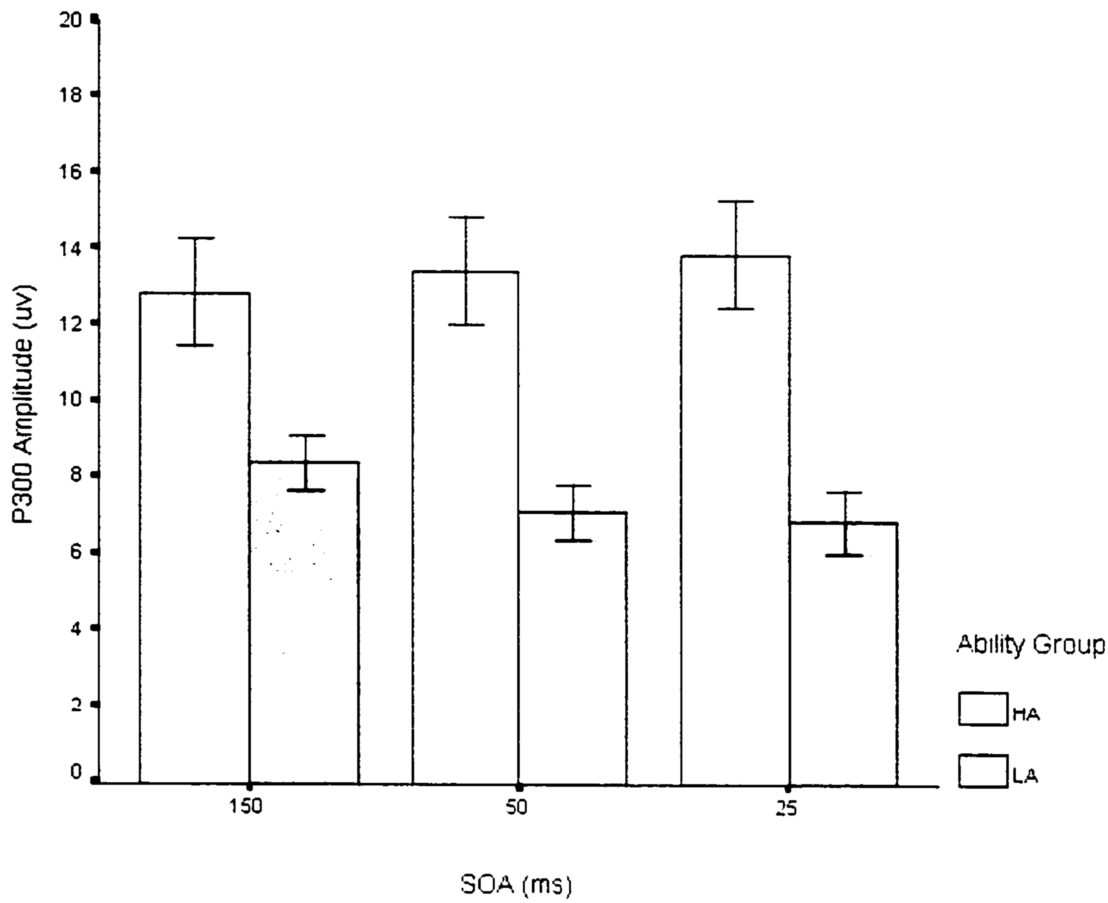


Figure 13

Plot of Means (SEs) for P3 Amplitude for Ability Groups at 150, 50, and 25 ms SOAs (N=24)



Intensity Manipulation

The intensity manipulation was expected to produce graded changes in behavioural performance and in the ERP measures. Specifically, it was anticipated that lower intensities would decrease percent correct detections for both groups, while increasing RTs and SDrts. Corresponding increases in P3 latency and MMN latency were also expected, as were decreases in P3 and MMN amplitudes. The manipulation of intensity levels, however, contributed no additional information to the analysis.

Overall, results in both the 82 and 76 dB conditions were identical to those from the 88 dB condition, with a few exceptions. A main effect of intensity on accuracy was observed ($F(2,44)=6.1$; $p<.01$), with 79.7% of deviants detected at 76 dB as compared with 84.9% at 88 dB (at 82 dB, 81.5% of deviants were detected). A main effect of intensity on RT was also uncovered ($F(2,44)=4.0$; $p<.05$), with RTs of 437.2 ms at 88 dB and 409.0 ms at 76 dB (reaction time at 82 dB was 417.3 ms). Similar results were found for P3 latency ($F(2,44)=5.6$; $p<.01$), with latencies of 423.7, 399.2, and 402.6 ms at 88, 82, and 76 dB, respectively. Finally, a 3-way interaction was observed for MMN latency ($F(4,88)=2.9$; $p<.05$). The interaction was found to occur between the ability group means at the 25 ms, 88 dB condition and the other conditions, where LA participants had significantly shorter latencies than HA participants (154.2 and 180.2 ms for LA and HA, respectively). No other effects of intensity were observed. Because the intensity manipulation added no new information, further analyses were not performed.

Power Analysis

Though post hoc, a power analysis will make it possible to determine if the weaker results in study 2 are a result of smaller sample size.

For mean RT to correct responses in study 1, an omega-squared value of .068 indicated a moderate strength of association and corresponds to a power level of .70 (at alpha = .05). Decreasing the sample size to 24, however, reduces power to .50. This means that the study has a 50-50 chance of detecting significant group differences in mean RT if such differences actually exist. A similar relation between sample size, strength of association (.112), and power (>.90) was apparent with percent correct responses, though the effect of reducing sample size was somewhat smaller. For standard deviation of RT, a large omega-squared (.127) corresponded to a power level larger than .90. With sample size reduced to 24, however, power was attenuated to .50. For experiment 1, an effect size of only .027 for number of false positives translates into a sample size of approximately 80 for a power level of .70. It is not surprising that no significant differences were detected.

Similar results were evident with P3 amplitude. Omega-squared in study 1 was .062, a moderate effect size and corresponding to a power level of about .70. When sample size is reduced to 24, power drops to .50. If the samples from studies 1 and 2 were combined, however, this would increase power to .90. An extremely small effect size was calculated for P3 latency, and it was determined that a few hundred participants would be required to detect group differences.

This was also the case with respect to MMN amplitude, where a small effect size (omega-squared = .015) indicated that a sample of approximately 270 individuals would be required to increase power to .80. With MMN latency, however, a moderate effect size indicated that a sample size of between 65 and 75 participants would result in a power level of about .70.

This analysis clearly demonstrates the lack of power in study 2, and, to a lesser extent, study 1. For this reason, it was necessary to combine samples from each study and restrict further analysis to identical conditions across studies (that is, use of only the 88 dB data from study 2).

COMBINED SAMPLE

Method

Participants

The samples from experiments 1 and 2 were combined for this analysis (a median split was not used), resulting in a sample size of 60. Individuals in the HA group had FIQ scores ≥ 114 (N=30; mean=121.0; SD=5.7); LA group participants had FIQ scores ≤ 112 (N=30; mean=106.0; SD=5.5).

Correlational analysis was extended with the combined sample to include the 10 subscales of the MAB, results of the 6 ZVT administrations, and grade. These variables were correlated with accuracy, number of false positives, RT, SDrt, P3 latency and amplitude, and MMN latency and amplitude; given the non-significant correlations between the N2b components and FIQ, N2b was not included in the extended correlational analysis.

In addition to the ANOVA and the extended correlational analyses, vector analyses were carried out in accordance with the methodology set forth in Jensen (1998). The g factor was defined in terms of the factor loadings of each individual intelligence subtest (10 MAB, 6 ZVT, grade) on the first unrotated factor in a principal components analysis. A hierarchical factor analysis was conducted using the ability variables and composite scores for the performance, and ERP variables. Vector analysis was conducted on P3 and MMN latency and amplitude measures.

Results

Means and standard deviations for all dependent variables are shown in Tables 9 to 11. Correlations between FIQ and all variables are shown in Table 13. Results of the extended correlational analysis are presented in Appendix A (Tables 10 to 17). Grand average waveforms for HA and LA ability groups for each SOA are shown in Figures 14 and 15 for attend and ignore conditions, respectively. Bar charts for percent correct detections, RT and P3 latency, and P3 amplitude are shown in Figures 16, 17, and 17, respectively. Results of the hierarchical factor analysis are reported in Table 18.

Performance Measures

Experimental Effect

There was no significant effect of SOA on percent correct detections, though SOA did influence RT with the combined sample ($F(2,116)=4.2$; $p<.05$). Specifically, longer RTs were observed at 150 ms (430.5 ms) than at 50 (406.7 ms) or 25 ms (406.1 ms). SOA had no influence on SDrt. Decreasing SOA produced significantly more false positives at 25 ms than at 150 ms ($F(2,116)=8.0$; $p<.001$).

Group Membership

Higher ability participants detected significantly more deviant tones than individuals in the LA group ($F(1,58)=16.3$; $p<.001$) at all SOAs. Higher ability participants had fewer false positives overall, though the differences were not significant.

The HA group also had significantly faster mean RTs to correct responses ($F(1,58)=7.6$; $p<.01$) at 150 and 50 ms SOAs, though the group difference approached significance at 25 ms ($p<.085$). Standard deviation of mean reaction time for each individual also varied inversely with ability ($F(1,58)=14.6$; $p<.001$), with HA participants showing more consistency in their responses at all SOAs. There was no ability group by SOA interaction for any of the discrimination task performance variables.

ERP Measures

Experimental Effect

With the combined sample, duration of the SOA had no influence on P3 latency or amplitude, nor on N2b amplitude. The 150 ms SOA produced a longer N2b latency (233.1 ms) than did the 25 ms SOA (219.5 ms), though the difference only approached significance ($p=.055$). The 150 ms SOA elicited a briefer MMN latency at 25 ms (172.8 ms) as compared with 150 ms (196.8 ms) ($F(2,116)=7.2$; $p<.01$). SOA had no effect on MMN amplitude.

Group Membership

Group differences in P3 latency were observed at 25 ms only ($F(1,58)=6.3$; $p<.05$). Higher ability participants exhibited larger P3 amplitude at all SOAs ($F(1,58)=14.2$; $p<.001$). There was no interaction between mental ability group and SOA on either P3 latency or amplitude.

Group differences in N2b latency were not significant, nor were there group differences in N2b amplitude. No interaction between SOA and group was observed for N2b amplitude.

Significant group differences in MMN latency were observed at the 25 ms SOA ($F(1,58) = 11.9$; $p<.01$). Differences in MMN amplitude were not apparent. There were no interactions between SOA and group membership on either variable.

Correlational Analysis

Correlational analyses again corroborated ANOVA results for performance variables, with all correlations in the expected directions. Here, however, significant correlations between FIQ and RT were observed at the 150 ms and 50 ms SOAs only ($r = -.44$, and $-.45$, respectively, both significant at $p<.05$). Significant correlations between FIQ and SDrt were observed at 150 and 25 ms. Correlational analyses for ERP measures in the attend condition were also consistent with ANOVAs with correlations between FIQ and P3 amplitude of .41 and .46

(both significant at p<.05) for the 50 and 25 ms SOAs only. A correlation of -.35 (p<.01) was observed between FIQ and MMN latency at the 25 ms SOA. In contrast with ANOVA results, a correlation of -.31 (p<.05) was observed between FIQ and MMN amplitude at the 25 ms SOA.

Vector Analysis

Only the vector analysis of P3 amplitude showed significant results. Correlations and rank-ordering of variables for the vector analysis of P3 amplitude are presented in the Appendix, Table 19. Results of the analyses are presented in the Appendix, Table 20. A scatterplot of the correlation of P3 amplitude with the subtests, plotted as a function of each subtests' g loading is presented in the Appendix, Figure 1.

Table 9

Means (SDs) for Discrimination Task Behavioural Performance Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=60)

	Correct Detections (%)		
	150	50	25
HA	91.1 (8.8)	89.2 (10.1)	88.8 (11.5)
LA	81.7 (11.8)	82.0 (11.7)	79.5 (11.5)
N=60	86.4 (11.3)	85.6 (11.5)	84.1 (12.3)
	False Positives		
	150	50	25
HA	1.8 (2.0)	3.7 (4.7)	5.4 (7.5)
LA	2.6 (5.0)	6.1 (9.2)	8.2 (10.2)
N=60	3.1 (4.0)	4.9 (7.3)	6.9 (9.0)
	RT (ms)		
	150	50	25
HA	396.1 (84.0)	376.2 (92.7)	382.5 (109.4)
LA	464.9 (86.4)	437.2 (87.1)	429.6 (98.0)
N=60	430.5 (91.3)	406.7 (94.4)	406.1 (105.6)
	SDrt (ms)		
	150	50	25
HA	112.7 (45.7)	105.0 (43.9)	102.3 (50.7)
LA	166.9 (58.5)	146.1 (68.8)	158.7 (82.6)
N=60	139.8 (58.8)	125.5 (60.8)	130.5 (73.7)

Table 10

Means (SDs) for P3 and N2b ERP Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=60)

	P3 Latency (ms)		
	150	50	25
HA	400.6 (68.8)	382.5 (55.8)	372.8 (65.2)
LA	421.1 (68.1)	404.1 (64.2)	420.4 (64.0)
N=60	410.8 (68.7)	393.3 (60.6)	396.6 (68.4)
	P3 Amplitude (μv)		
	150	50	25
HA	14.0 (6.8)	14.6 (7.7)	14.8 (9.1)
LA	8.9 (5.1)	8.2 (5.3)	8.1 (4.7)
N=60	11.5 (6.5)	11.4 (7.3)	11.5 (7.9)
	N2b Latency (ms)		
	150	50	25
HA	231.5 (42.0)	218.6 (35.2)	219.2 (41.3)
LA	234.8 (43.4)	229.1 (45.5)	219.8 (35.2)
N=60	233.1 (42.4)	223.9 (40.7)	219.5 (38.1)
	N2b Amplitude (μv)		
	150	50	25
HA	5.1 (4.2)	4.7 (3.8)	4.3 (6.1)
LA	5.6 (4.0)	5.6 (4.1)	4.6 (3.9)
N=60	5.3 (4.1)	5.2 (3.9)	4.6 (4.5)

Table 11

Means (SDs) for MMN ERP Measures for Ability Groups at 150, 50, and 25 ms SOAs (N=60)

	MMN Latency (ms)		
	150	50	25
HA	189.2 (33.7)	184.8 (30.2)	160.1 (36.0)
LA	204.4 (28.1)	194.1 (41.5)	185.4 (36.4)
N=60	196.8 (31.7)	189.4 (36.3)	172.8 (38.1)

	MMN Amplitude (µv)		
	150	50	25
HA	2.0 (2.5)	2.1 (1.8)	2.3 (2.3)
LA	2.0 (1.9)	1.9 (1.8)	1.8 (2.4)
N=60	2.0 (2.2)	2.0 (1.8)	2.1 (2.4)

Table 12

Correlations between Full-scale IQ and Performance and ERP Measures at 150, 50, and 25 ms SOAs (N=60)

	SOA		
	150	50	25
Discrimination Task Measures			
Percent Correct Detections	.42 **	.31 *	.43 **
False Positives	-.30 *	-.07	-.08
RT	-.44 **	-.45 **	-.27 *
SDrt	-.54 **	-.39 **	-.38 **
ERP Measures – Attend			
P3 Latency	-.13	-.28 *	-.45 **
P3 Amplitude	.34 **	.41 **	.36 **
N2b Latency	-.07	-.15	-.01
N2b Amplitude	-.06	-.01	-.01
ERP Measures – Ignore			
MMN Latency	-.14	-.15	-.35 **
MMN Amplitude	-.01	-.24	-.31 *

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

Figure 14

ERP Waveforms and RT Histograms for Ability Groups during the Active Condition, 150, 50, and 25 ms SOAs (N=60)

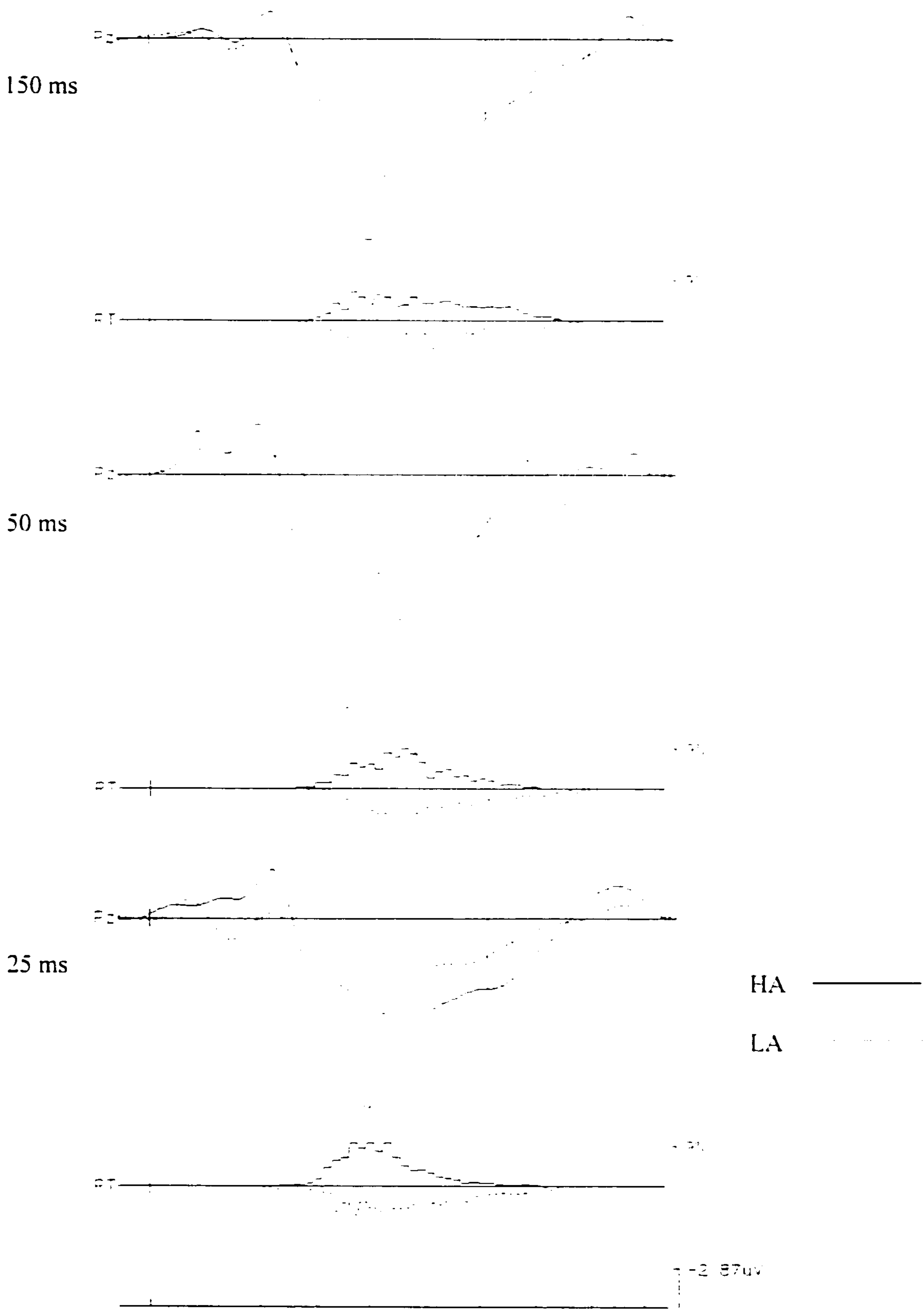


Figure 15

<u>ERP Waveforms for Ability Groups during the Passive Condition, 150, 50, and 25 ms SOAs (N=60)</u>

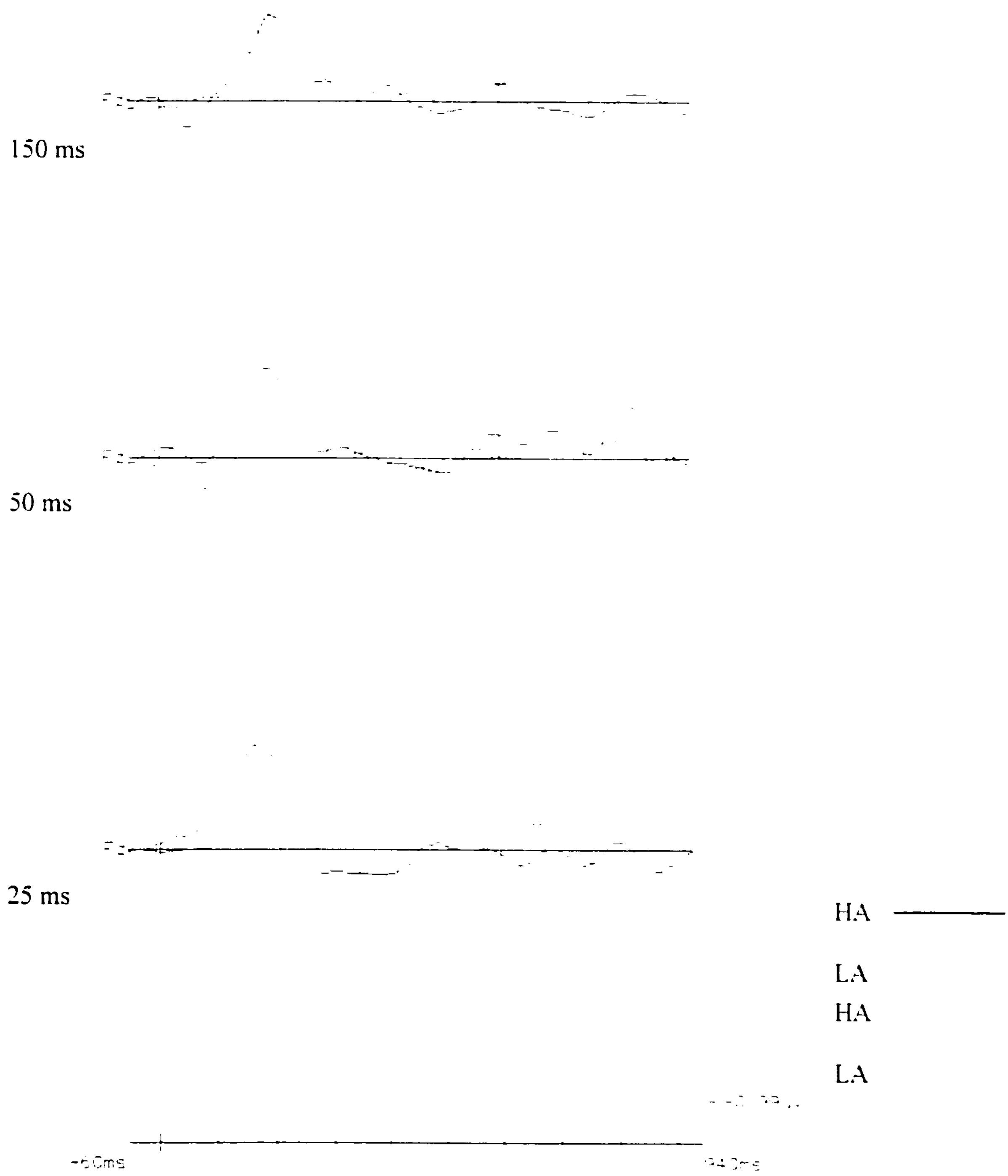


Figure 16

Plot of Means (SEs) for Percent Correct Detections for Ability Groups at 150, 50, and 25 ms SOAs (N=60)

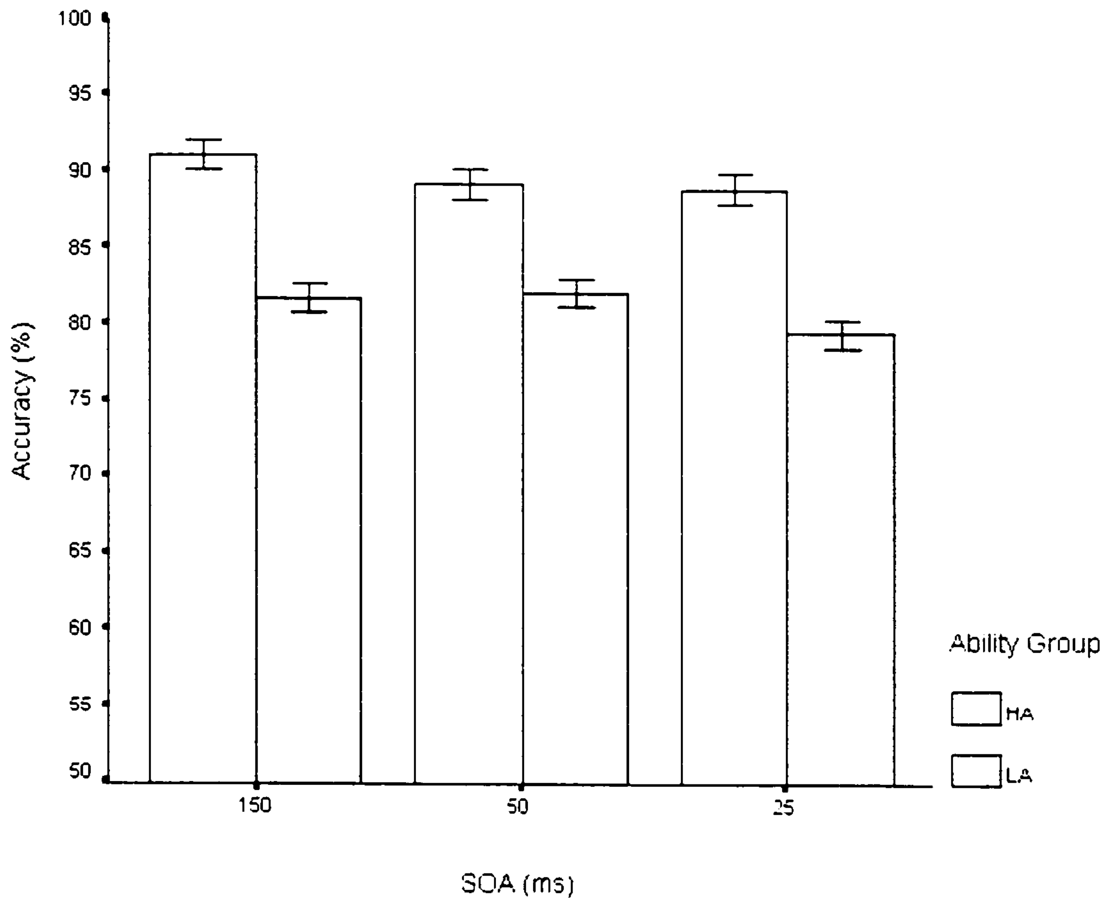


Figure 17

Plot of Means (SEs) for RT and P3 Latency for Ability Groups at 150, 50, and 25 ms SOAs (N=60)

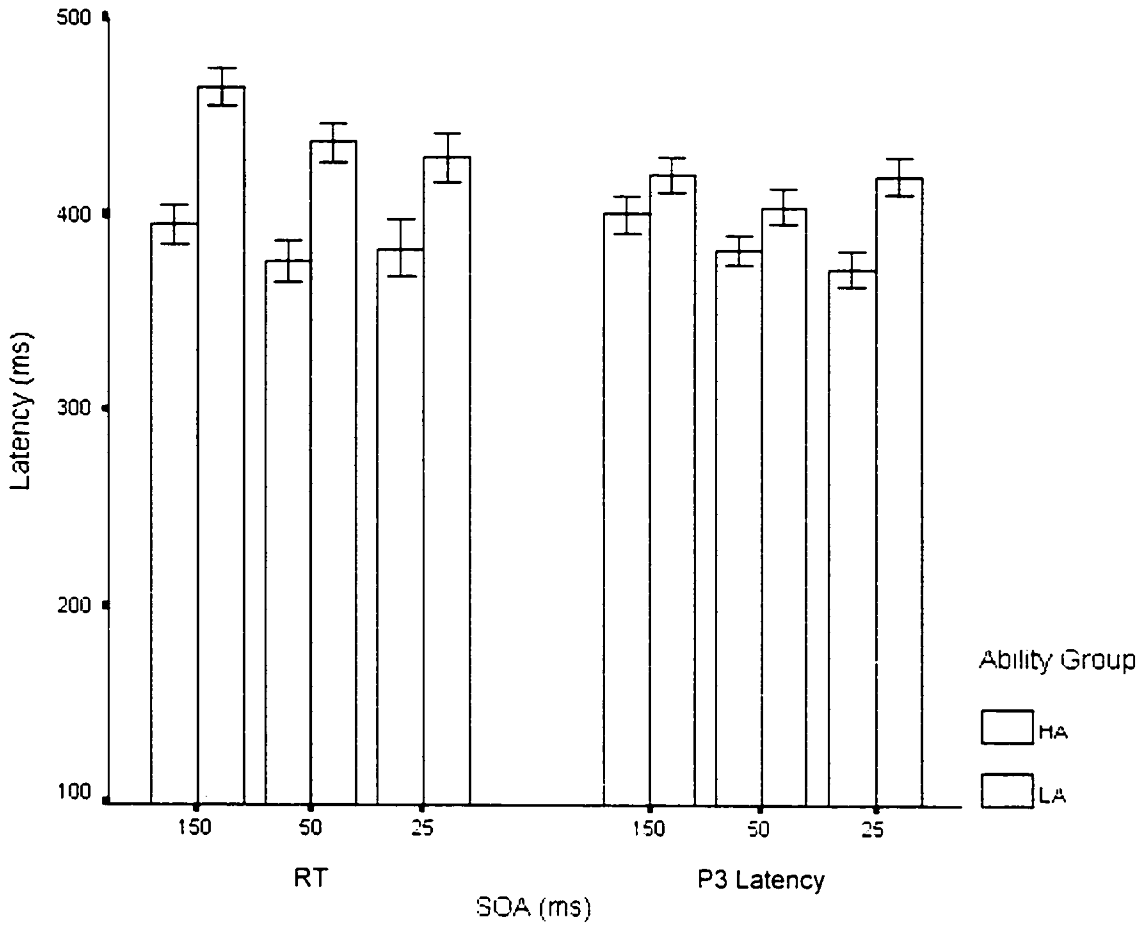
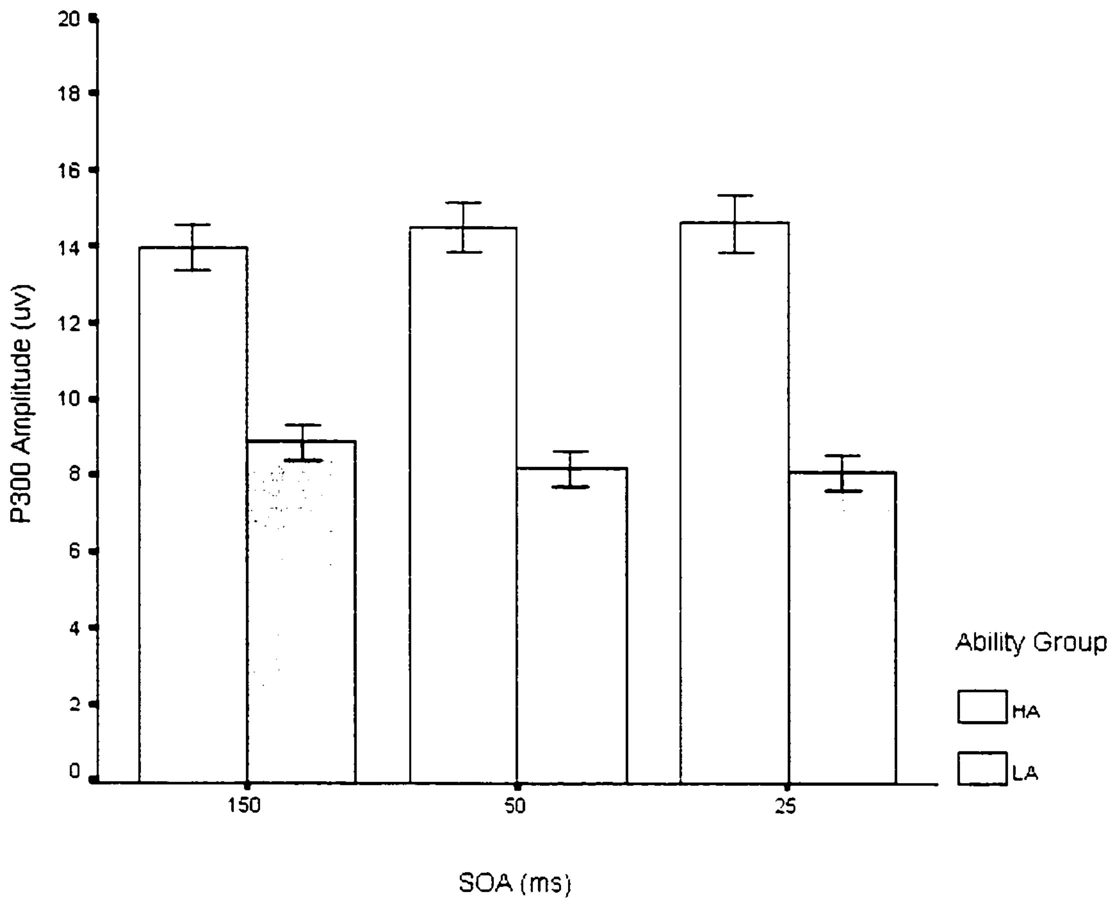


Figure 18

Plot of Means (SEs) for P3 Amplitude for Ability Groups at 150, 50, and 25 ms SOAs (N=60)



Discussion

In the present studies, a new paradigm, the backward-masked auditory oddball procedure (Winkler et al., 1993), was introduced to the study of intelligence. It was anticipated that HA participants would exhibit superior performance: more accurate detection of deviants, more error-free processing (fewer false positives), faster processing, as indexed by RT, and smaller intra-individual differences in responding across trials (SDrt). It was also expected that physiological indices, specifically P3 and MMN latencies, would bear some relation to the intelligence measures. Expectations regarding group differences in amplitude were somewhat indeterminate for P3, as well as for MMN.

Overall, many of these expectations were met. Higher ability individuals consistently detected more deviant tones than LA subjects. Higher ability participants had fewer false positives. The HA group exhibited faster RTs than the LA group at all SOAs, and had more consistent RTs from trial to trial. For the physiological indices, HA subjects had larger P3 amplitudes, and trends for P3 latency were in the expected directions.

In study 1, the HA group detected significantly more deviant tones than the LA group in the 150 ms condition only (though differences approached significance at 50 and 25 ms SOAs); in study 2 group differences were significant at all SOAs. In study 1, significant group differences in mean RT were observed at 150 and 50 ms SOAs, while in study 2 there were no significant effects of group at any SOA. Group differences in SDrt were generally concordant, though in study 2 the effect was only significant at 150 and 25 ms SOAs. For the physiological measures, significant differences in P3 latency were observed in study 1 at the 25 ms SOA; in study 2, group differences were non-significant at all SOAs (though trends were as anticipated). Group differences in P3 amplitude were significant at all SOAs in study 1, but only at 50 and 25 ms SOAs in study 2. Finally, for MMN, group differences in latency or amplitude were not observed in study 1. In study 2, group differences in latency were observed at the 25 ms SOA.

In general, group differences observed in study 1 were somewhat less evident in study 2. It is likely that the non-significant ANOVA results for RT, SDrt, and some ERP measures at the 3 SOAs in study 2, are a result of inadequate power. Though results in study 1 suggested large effect sizes, power analyses indicated that the effect was not quite as robust as might have been expected. This occurred because smaller sample size reduced power for even the largest effect sizes by .20 to .30 from study 1 to study 2. Moreover, in study 2, reducing the total number of blocks per condition by one-half introduced substantially more error variance. This is partly demonstrated by larger mean square variance values for some of the ANOVAs in study 2. Because of the influence of insufficient power, and for clarity of interpretation, the discussion will focus on the combined sample.

Accuracy

In accordance with Raz et al. (1983, 1985), the present study predicted that if HA participants were superior in rapid auditory information processing, it would be greater at shorter SOAs. At the longer SOA (150 ms), it was expected that both groups would have similar performance because all individuals would have enough time to make the discrimination correctly. Raz et al. (1983) note that "the mechanism, or mechanisms, to account for group differences in auditory recognition would ... reflect differences in efficiency of information processing and specifically, higher signal-to-noise ratios in the high aptitude subjects" (Raz et al., 1983, p.74). Moreover, it was expected that group differences in discrimination ability would be accentuated under conditions where backward masking produced graded changes in discriminability of the tones. In other words, it was hypothesized that performance of LA subjects would decrease precipitously as SOA decreased from 150 to 50 to 25 ms, while HA subjects would maintain a higher degree of performance at even the shortest SOA.

Significant group differences were apparent at all SOAs for the combined sample, with HA individuals consistently detecting more deviant tones than LA subjects. Decreasing SOA did not produce the anticipated, graded changes in accuracy, particularly for the LA group (which had 81.7, 82.0, and 79.5% accuracy in the 150, 50, and 25 ms conditions, respectively, compared with 91.1, 89.2, and 88.8%, respectively, for the HA group), though trends in the expected direction were evident. Correlations between FIQ and accuracy were 0.42 ($p<.01$), 0.31 ($p<.05$), and 0.43 ($p<.01$) for 150, 50, and 25 ms SOAs, respectively. Taken together, results suggest that all participants, regardless of FIQ score, found the task relatively easy.

False positives

HA subjects tended to have fewer false positives than LA subjects. As expected, decreasing SOA produced a significantly greater number of false positives in the most difficult condition (25 ms SOA) for the combined sample. Overall, however, there were very few false positives for either group, which, along with the high degree of accuracy for both groups at all SOAs, indicate that the task was not difficult, even at the shortest SOA.

Reaction Time

Reaction time is the interval between the onset of the stimulus to be classified or discriminated and the initiation of the cognitive response of the subject (Jensen, 1993). The response is typically a button press. Results for RT accorded with studies relating RT with intelligence (Jensen, 1987, 1993; Vernon, 1987, 1990). The HA group had faster RTs to detected deviants than the LA group at all SOAs (correlations of -.44 ($p<.01$), -.45 ($p<.01$), and -.27

($p<.05$) for 150, 50, and 25 ms SOAs, respectively). The differential speed of responding for the two groups lends support to the SIP view of psychometric ability.

An unexpected result, however, was the inverse relation between decreasing SOA and longer RTs. Even if the effect of task difficulty was negligible (which, on the basis of the accuracy data, is a reasonable conclusion), RTs could have been expected to be the same across all SOAs (because the duration of the standard and deviant tones was held constant at 25 ms). Reaction times, however, were significantly longer for both groups at 150 ms than at 50 or 25 ms SOAs. This suggests that some participants did not base their responses solely on the pitch of the deviant tone but rather on some combination of the tone and the mask. Only after both the deviant (or standard) tone *and* the mask had been processed was a decision made regarding whether or not to respond.

SDrt

The standard deviation of an individual's RTs across trials within a condition (SDrt) refers to intra-individual variability, or consistency, of responding across trials: SDrt increases with increasing task difficulty. It has been widely reported that individuals of higher intelligence have smaller SDrts than those of lower ability (see Jensen, 1998).

The HA group had significantly smaller SDrts at all SOAs. The largest group differences were apparent at 150 ms. Correlational analysis yielded values of -.54 ($p<.01$), -.39 ($p<.01$), and -.38 ($p<.01$) for 150, 50, and 25 ms SOAs, respectively. There was no experimental effect of SOA.

Overall, these results support the conclusion that decreasing SOAs did *not* correspond to increasing task difficulty.

P3 Latency

The latency of P3 indexes the chronometry of the cognitive operation of stimulus evaluation and classification (McCarthy & Donchin. 1983). It is a useful adjunct to RT because it provides a measure of SIP that is relatively independent of response selection and production (Howard & Polich. 1985: McCarthy and Donchin. 1981: Verleger. 1997). Like RT. P3 latency increases with increasing task difficulty (Duncan-Johnson & Kopell. 1981: McGarry-Roberts et al.. 1994) and varies inversely with intelligence (McGarry-Roberts et al.. 1994).

In the present studies. significant group differences were apparent at the 25 ms SOA (HA = 372.8 ms: LA= 420.4 ms). Decreasing SOA increased P3 latency for the HA group (from 400.6 to 372.8 ms at 150 and 25 ms SOAs. respectively). Correlations between ability and P3 latency increased from -.13 (non-significant) to -.28 ($p<.05$) to -.45 ($p<.01$) as SOA decreased from 150 to 50 to 25 ms. respectively. The systematic increase in magnitude from longest to shortest SOA might be taken to indicate that HA participants were able to evaluate and classify the stimuli more rapidly with decreasing SOA.

P3 Amplitude

As outlined in the literature review. the functional significance of P3 amplitude as it relates to intelligence is an unresolved issue. Because higher amplitude is suggestive of greater information extraction (Johnson. 1986. 1988b). it has been proposed that HA individuals have higher amplitudes than LA individuals in various ECTs. It may also be that more intelligent individuals use their cognitive resources more efficiently. though. thereby reducing P3 amplitude in some conditions. Implicit in this. of course. is the assumption that individuals who use their cognitive resources 'more efficiently' also make better use of their use their 'neuronal resources'. Intelligence studies employing P3 are about evenly divided on the issue.

In the present experiments, HA subjects had larger P3 amplitudes at all SOAs. Previous research has shown that P3 amplitude decreases with increasing task difficulty (Johnson, 1988b). Here P3 amplitude of subjects in the HA group increased slightly with decreasing SOA, while LA subjects' P3 amplitudes decreased slightly (though not significantly) as SOAs became shorter. Correlations between P3 amplitude and FIQ in the .34 to .41 range were observed across SOAs.

Overall, these results might indicate that HA participants extracted more information from the set of stimuli and were therefore better able to make more correct discriminations (and fewer incorrect ones) than LA individuals. Given that little information was conveyed in the discrimination task, though, this interpretation is speculative at best.

MMN Latency

The MMN indexes the contents of the auditory buffer, also known as echoic memory; MMN is an automatic deviance-detector mechanism because it is elicited only by deviant tones, and not by standards in an auditory oddball task. Its latency indicates the speed with which the deviant stimuli has been classified as differing from the standard tone in sensory memory.

Overall, decreasing SOA resulted in shorter MMN latency. The difference in MMN latency between the 150 and 25 ms SOAs for the entire group (N=60) was significant. Latency decreased from 196.8 to 189.4 to 172.8 ms from longest to shortest SOA. A trend toward HA individuals having faster latency was observed, with significant group differences found at the 25 ms SOA. The FIQ – MMN latency correlation for this SOA was -.35 ($p<.05$).

Taken together, these results suggest that HA individuals process information in the sensory buffer more rapidly. This would facilitate decision-making in simple discrimination tasks. If more information is available in the echoic memory of HA individuals, because of enhanced speed, then more intelligent individuals have an advantage when a decision is made to respond. Specifically, transfer of the contents of echoic memory to STM may be facilitated because more information is available to be conveyed.

MMN Amplitude

Amplitude of the MMN reflects the strength of the memory trace in the echoic buffer (Naatanen & Winkler, 1999). Given the relations between MMN amplitude and behavioural performance in the Winkler et al. study (1993), it is reasonable to expect that higher ability individuals would have larger amplitudes. This would reflect, as Winkler et al. note, "a stronger memory trace", a prerequisite for superior performance within the context of their interpretation.

This effect was observed at 25 ms SOA only. HA and LA groups had identical amplitudes at 150 ms (2.0 μv), and groups differed by only .20 μv at 50 ms. At 25 ms, however, a .50 μv difference was observed, a substantial difference in amplitude for this ERP component. The correlation between MMN amplitude and FIQ was -.31 ($p<.05$). Note that the correlation is negative because the MMN is negative-going, that is, HA subjects actually had larger amplitudes at this SOA. Thus, as with MMN latency, ability-group differences were apparent only at the briefest SOA.

Extended Correlational Analysis

The extended correlational analysis revealed some interesting patterns of correlations. In general, verbal subscales were better predictors of discrimination accuracy than performance subscales across the 3 SOAs. This was also the case with verbal-RT correlations at 150 and 50 ms. Both verbal and performance subscales had higher correlations with SDrt at longer SOAs. Grade was a generally poor predictor of performance.

For the ERP latency measures, verbal subscales and P3 latency had negligible concordance. Performance subscales for digit symbol, spatial, and object recognition increased in magnitude as SOA decreased. A weak pattern of correlations between performance subscales and MMN latency was observed at the 25 ms SOA; no pattern was evident at the other SOAs. Arithmetic and comprehension verbal subscales correlated with P3 amplitude, while digit symbol, picture arrangement, and object recognition performance subscales had moderate concordance with P3 amplitude overall. Only two significant correlations between ability and MMN amplitude were observed.

In general, the more complex and difficult versions of the ZVTs (ZVT-G and ZVT-L) correlated more highly with accuracy, number of false positives, and RT. For SDrt all but one of the six ZVT administrations produced moderately large correlations (.26 to .48 in absolute magnitude). For P3 latency, the magnitude of the correlations ranged from .20 to .38 in the 25 ms condition only. Time-to-complete administrations of each ZVT version correlated about -.33 with P3 amplitude. Finally, ZVT-MMN correlations were small, though they tended to be larger for the 25 ms SOA.

Hierarchical Factor Analysis

The hierarchical factor analysis produced 5 primary factors. The first factor was comprised of the digit symbol, spatial, and object assembly performance subscales, along with P3 and MMN latencies and accounted for 25.1% of the variance. Percent correct responses, RT, and SDrt comprised a second, relatively unambiguous factor (along with loadings on grade and arithmetic), which accounted for 13.2%. The structure of the third factor extracted was less clear. Here picture completion and picture arrangement (both performance subscales) loaded on the same factor as P3 amplitude (as did comprehension, a verbal subscale). The fourth factor consisted of the verbal subscales and MMN latency, while the fifth was composed of the ZVT composites and MMN amplitude. The higher-order factor, psychometric g, accounted for 38.3% of the variance.

Vector Analysis

The method of correlated vectors is designed to elucidate the relation between psychometric g and a physiological variable. Vector analysis tests whether the g factor extracted from a battery of diverse tests is related to another variable that is external to that test battery (Jensen, 1998). The technique is often used to determine the relation between psychometric g and some biological variable thought to be related to g (Schafer, 1985). "If the degree to which each of the various tests is loaded on g significantly predicts the relative magnitudes of the various tests' correlations with the external (biological) variable.... then it is concluded that (the biological) variable...is related to g (regardless of whether or not it is related to other factors of test specificity)" (Jensen, 1998, p.589).

Overall, the correlations were substantial and in the expected direction. Results indicate a moderately strong relation between P3 amplitude and intelligence (see Table 10, Appendix). Of particular note is the Pearson correlation between the subtests' corrected g-loadings (in the column designated C), and the subtests' corrected correlation with P3 amplitude (in the G column). The correlation of .409 just fails to reach significance (p=.052). Moreover, the relative ranking of the subtests' corrected g-loadings and their corrected correlation with P3 amplitude has a correlation of .439 (p=.039). When the effects of the corrections for attenuation are partialed out, the correlations are reduced only slightly.

Examination of the scatterplot of the correlations between P3 amplitude and each of the MAB subtests, ZVT tests, and grade (plotted as functions of the subtests' g loading; Figure 1, Appendix) is helpful in interpreting results. Data points in the upper right quadrant are of particular interest. The "L" version of the ZVT (45 second administration) has a very high g-loading, and correlates about .30 with P3 amplitude. In the time to complete versions of the ZVT-L (L_{all}) and ZVT-G (G_{all}), g-loadings are slightly smaller (about .68) though correlations with P3 amplitude increase slightly. Two performance subscales, spatial and digit symbol, have g-loadings of about .67 and correlate moderately with P3 amplitude.

Overall, the results suggest that some performance measures, which are tests of fluid intelligence, bear more relation with P3 amplitude than verbal ability tests. The ZVT tests, which are brief, simple, and speeded, probably measure SIP in STM (Vernon 1993); more complex versions have the strongest association with P3 amplitude. Though these results are interesting, these relations are also evident in the extended correlational analysis.

Personality and Intelligence

The possibility that personality might mediate the relation between intelligence and behavioural performance or ERP measures was examined (Cahill & Polich, 1992; Ditraglia & Polich; Polich & Martin, 1992; Pritchard, 1989; Socan & Bucik, 1998; Stelmack, Houlihan, & McGarry-Roberts, 1993). Personality scores on the EPQ-R (Eysenck & Eysenck, 1985) were correlated with performance and ERP measures. The analysis revealed significant correlations between the Psychoticism (P) scale and RT and SDrt at all SOAs. Concordance between P and RT was .31, .36, and .45 for 150, 50, and 25 ms SOAs, respectively; for SDrt, correlations of .29, .39, and .36 were observed. Scores for Extraversion (E) also correlated with RT and SDrt, but only for the 50 ms SOA ($r = .35$ for RT, $r = .26$ for SDrt). Finally, P3 latency in the 50 ms condition correlated with P scores ($r = .30$).

Partial correlation analysis was performed with the effects of P partialed out and concordance between FIQ and RT and SDrt for each SOA assessed. Of the six correlations, only one dropped to non-significance: the correlation between FIQ and RT at 25 ms decreased from -.27 ($p<.01$) to -.20 ($p=.137$). The correlation between FIQ and P3 latency in the 50 ms SOA condition also decreased significantly, from -.28 ($p<.05$) to -.23 ($p=.079$). When E was controlled for, no significant changes were observed.

Other Factors Mediating Performance and ERP Measures

Many factors have been shown to influence the variables assessed in the current research. This overview focuses on factors moderating P3, but many of the confounds also affect behavioural performance and even IQ scores (Iragui, Kutas, Mitchiner, & Hillyard, 1993). Age-related declines in fluid intelligence but not crystallized intelligence have been reported (Schretlen, Pearlson, Godfrey, Anthony, Aylward, Augustine, Davis, & Barta, 2000).

Age influences P3 latency and amplitude. Picton et al. (1992; Picton, Stuss, Champagne, & Nelson, 1984) report a linear increase of about .90 to 1.70 ms in P3 latency per year for adults; decreases in P3 amplitude have also been reported (Fabiani & Friedman, 1995; Osawa, 1995; Picton, 1992). Polich (1996), in a meta-analysis of normative aging studies and P3, noted similar findings, though task characteristics and electrode placement had some bearing on the results. Participants in the present studies had a mean age of 20.1 (SD = 3.1) for the experiment 1 sample and a mean age of 19.8 (SD = 3.3) for experiment 2. With this highly limited range, age was not a confound in the current research.

Gender has been shown to influence P3 amplitude, but not latency. Males have smaller P3 amplitudes in auditory oddball tasks (Cahill & Polich, 1992; Ditraglia & Polich, 1991; Polich & Martin, 1992), an effect attributed to males having thicker skulls and larger brain volumes.

Again, because the studies reported here used only females, gender was not a confound. Handedness also influences responding (Brunswick & Rippon, 1994). Specifically, lateralization of the ERP waveform is affected differentially by right- or left-handedness. Hence, the current research employed only right-handed individuals. Another obvious confound is language: involving only individuals who spoke English as a 1st language obviated problems with understanding instructions for completing the psychometric instruments and for correct performance on the behavioural task.

Many psychoactive substances have been demonstrated to influence P3 (Loring & Meador, 1989; Meador, Loring, & Davis; Milligan, Lumsden, Howard, Howe, & Dundee, 1989). Consequently, subjects taking psychoactive medications were excluded from the study. Nicotine (Landers, Lindhold, Crews, & Koriath, 1990; Norton, Howard, & Brown, 1991), caffeine (Lorist, Snel, & Kok, 1994a; Lorist, Snel, Kok, & Mulder, 1994b), and alcohol (Lukas, Mendelson, Kouri, Bolduc, & Amass, 1990) have all been shown to influence behavioural performance and ERPs on various ECTs. Therefore, subjects were instructed to abstain from these substances for at least 24 hours prior to behavioural and ERP data collection. Participants were asked upon arrival at the testing session whether they had complied with this requirement; all subjects responded in the affirmative. To assess the possibility that performance was affected by deficiencies in hearing, all participants were tested for normal hearing (15 dB ISO) at 500, 1000, 1500, and 2000 Hz.

Finally, two other factors are addressed: menstrual cycle and time of day. Data on menstrual cycle was collected for participants in the second study only (and was recorded as number of days between beginning of last cycle and the day of ERP testing), as was morning-evening preference (measured as time of day in minutes past midnight).

Studies on menstrual cycle have reported that ECTs having affective content increase P3 amplitude during ovulation (Johnston & Wang, 1991). Typically, however, more standard ECTs (e.g., the auditory oddball), produce no variation in ERP measures (Fleck & Polich, 1988). No significant correlations were observed between menstrual cycle and any other measure for the participants in experiment 2. Interestingly, though, patterns of small negative correlations were found between cycle and accuracy, SDrt, and P3 amplitude. Specifically, number of days since beginning of last cycle correlated -.26, -.20, and -.16 with accuracy in the 150, 50, and 25 ms SOA conditions, respectively; with SDrt, correlations were -.13, -.11, and -.12 over the same SOAs; for P3 amplitude, correlations were -.19, -.17, and -.21. These correlations are relatively small, and level of significance for the largest correlation is only $p<.28$. That concordance is consistently negative for each variable, however, suggests that further research on the impact of hormonal changes associated with menstruation on ability-related variables is indicated.

There is some evidence that time-of-day may mediate both test scores and performance (Song & Stough, 2000). In the present research, however, correlations between time of day and ability measures were non-significant ($r = .11$), as were correlations between accuracy ($r = .03$) and RT ($r = .05$). Examination of the influence of time of day on P3 amplitude (Geisler & Polich, 1992) and latency also revealed no significant correlations ($r = .16$ and $r = .06$ for P3 amplitude and latency, respectively). Correlations between MMN amplitude and latency were .17 and .07, respectively (both non-significant).

Even with these precautions, however, some characteristics of the sample may still have affected the study outcomes. A potential problem with the sample is that all subjects were first year introductory psychology students. It is conceivable that some individuals were motivated by a general interest in this type of study, that is, a self-selection bias may have been operative. To engender interest, participants were told that they would receive a printout of their "brain waves". Participants were also clearly aware that personality and intelligence inventories were important. That these were potentially related to the brain waves was equally obvious. Moreover, the laboratory setting may have provided a new, interesting, and stimulating environment, especially for psychology students in their first year of university. Consequently, subjects may have been motivated to do their best on the behavioural task. Many studies have addressed this problem, and the well-known phenomenon of the "social psychology of the psychology experiment" cannot be discounted in the current research. Because MMN is elicited in the absence of conscious awareness, however, problems of this type are mitigated in the ignore condition.

Another significant confound is restriction of range. The samples were a full standard deviation above the norm (mean FIQs of 113.2 (SD = 9.7) in experiment 1, 114.0 (SD = 9.0) in experiment 2, 113.5 (SD = 9.4) for the combined sample). Restriction of range was not corrected for in the present research. A compensatory factor, though, is that HA and LA groups also differed by about one standard deviation across the studies ($p<.001$ in Studies 1 and 2, and for the combined sample). This result informs the present studies in that groups were probably better classified by the designation of average ability (AA) and higher ability (HA).

Summary and Interpretation

Overall, higher ability participants performed better, processed information more rapidly and may have processed more information (as evidenced by larger P3 amplitudes) than those of lower ability. The experimental manipulation of SOA was only effective in a few cases, however. In particular, P3 latencies for the HA group decreased with decreasing SOA (400.6 ms at 150 ms SOA; 382.5 ms at 50 ms; 372.8 at 25 ms SOA). P3 latencies for the LA group were

421.1 ms, 404.1 ms, and 420.4 ms for 150, 50 and 25 ms SOAs, respectively. An obvious question raised in the present research is whether HA and LA subjects performed the task differently in some way.

One possibility is that some subjects adopted a cognitive strategy while performing the discrimination task (Simpson & Deary, 1997; Wittlied-Verpoort & Perret, 1987). Higher ability participants may have responded to the difference in pitch between the standard and the deviant while (some) LA individuals may have compared the standard and deviant with the mask. This might account for the systematic decreases in P3 latency for the HA group, who did not, in a sense, wait for the offset of the mask to classify the deviant tones, and also for the long latency at 25 ms for the LA group, who may have processed the tones and mask as a unit. The RT data lends some support to this interpretation; because movement time was not recorded, however, this support is tentative. SDrt results are more informative. If a subset of LA subjects adopted the strategy of comparing the tone with the mask (or if some LA participants did so part of the time), then SDrt for the LA group overall would be larger than for the HA group, which is what was observed.

If a relation exists between MMN and intelligence, and if ability-related differences in IT task performance are influenced by characteristics of the MMN, then these relationships should be most apparent in the correlations between MMN components and fluid rather than crystallized ability (Deary, 1993; Kranzler & Jensen, 1989; Nettelbeck, 1987). This was the case, particularly for MMN latency (see Appendix, Table 7) The possibility also exists that the observed relations between intelligence and MMN were merely spurious. Because the MMN and P3 ERP components form part of a complex, with N2b occurring "between" them in the active condition, it would be quite reasonable to expect ability-related latency effects for N2b, at least where such effects were observed for MMN (i.e.. at the 25 ms SOA). These were not apparent. Further research is clearly warranted.

Directions for Further Research

Much has been written in the past 20 years on the theoretical underpinnings of ability-related performance in auditory discrimination tasks. This is particularly evident with AIT. whether or not ERPs are used. Aside from the present research. no study to date has exploited the vast literature of cognitive psychophysiology. Attempts at understanding ability-related differences in sensory processes must begin with ERP components known to index these operations.

The manipulation of SOA (Raz et al.. 1983. 1985) rather than stimulus duration would likely yield greater insight into the relationship between ability and auditory discrimination. A rich literature built on the seminal work of Massaro (1971. 1972a. 1972b. 1973a. 1973b). Another potentially fruitful avenue is using variations in loudness instead of pitch in IT and IT-type tasks (Olsson et al.. 1998). As Schroger (1996) points out. the MMN generated by differences in intensity has characteristics quite distinct from the MMN elicited by frequency differences. The use of deviant tones differing in loudness instead of frequency obviates valid criticisms of performance in the AIT task as being dependent on pitch discrimination ability as opposed to factors related to SIP (Caryl. Golding. & Hall. 1995: Deary. 1994: Deary. Head. & Egan. 1989: Irwin. 1984: Langsford. Mackenzie. & Maher. 1994).

Conclusions

The present studies were undertaken to explore the differences between HA and LA individuals on behavioural performance and ERP measures using a new task. the backward-masked auditory oddball paradigm (Winkler & Naatanen. 1993). Event-related potentials recorded in the attend condition elicited P3 and provided insight into the operations of STM. in particular the process of stimulus evaluation and classification. Event-related potentials recorded in the ignore condition elicited MMN. and allowed examination of the contents and speed of operation of the echoic buffer. Overall. the general findings of Raz et al. (1983. 1985) have been endorsed.

The present research was successful in distinguishing HA and LA groups. both behaviourally and psychophysiologically. The paradigm and the results reported in this paper build on a robust body of research in cognitive psychophysiology and mental chronometry. Further research building on this literature will help to elucidate the relation (and relations) between individual differences in psychometric intelligence and characteristics of the individual brain.

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Appendix

Table 1

Descriptive Statistics for Psychometric Variables. Experiment 1 (N = 36)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	113.2	9.7	95	134	0.17	-0.49
VIQ	109.5	7.4	94	126	-0.07	0.04
Information	23.6	4.2	16	33	0.30	-0.20
Comprehension	20.1	2.8	15	26	0.19	-0.67
Arithmetic	13.4	2.2	6	17	-1.22	3.07
Similarities	24.9	4.8	8	31	-1.99	4.91
Vocabulary	23.2	7.1	11	38	0.32	-0.44
PIQ	115.9	13.3	90	141	-0.20	-0.72
Digit Symbol	27.1	3.8	18	34	-0.17	-0.21
Picture Completion	22.3	3.7	12	27	-0.66	0.18
Spatial	30.9	8.8	5	47	-0.62	0.74
Picture Arrangement	12.4	1.9	8	16	-0.57	0.09
Object Assembly	14.1	3.9	6	19	-0.62	-0.84
ZVT $1\text{-}2\text{-}3_{45}$	71.4	14.3	45	90	-0.26	-1.26
ZVT $179\text{-}177_{45}$	28.9	11.2	4	49	-0.39	-0.72
ZVT $Z26\text{-}Y25_{45}$	22.9	18.6	3	90	2.44	6.92
ZVT $1\text{-}2\text{-}3_{all}$	58.6	14.9	39	114	1.73	4.32
ZVT $179\text{-}177_{all}$	100.9	25.8	61	162	0.73	-0.46
ZVT $Z26\text{-}Y25_{all}$	227.1	93.4	102	480	0.92	0.23
Grade (previous year)	3.6	0.7	2	5	0.23	-0.21
EPQ P	5.8	3.0	2	15	0.94	0.98
EPQ E	16.4	5.2	3	22	-0.83	-0.10
EPQ N	15.0	5.3	3	23	-0.41	-0.63
EPQ L	5.5	3.4	0	14	0.63	-0.02

Table 2

Descriptive Statistics for Psychometric Variables, Experiment 1, Higher Ability Group (N = 18)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	121.0	6.1	114	134	0.68	-0.28
VIQ	114.2	5.5	106	126	0.55	-0.36
Information	24.8	4.3	20	33	0.76	-0.81
Comprehension	20.6	3.2	15	26	-0.04	-0.88
Arithmetic	14.2	1.7	12	17	0.12	-0.97
Similarities	27.1	2.1	23	31	-0.20	-0.34
Vocabulary	24.0	7.3	11	38	0.40	-0.04
PIQ	125.9	8.0	107	141	-0.25	0.69
Digit Symbol	29.4	2.9	24	34	-0.03	-0.77
Picture Completion	23.4	3.7	12	27	-1.92	4.85
Spatial	35.9	6.5	25	47	-0.47	-0.54
Picture Arrangement	13.3	1.4	11	16	0.03	-0.61
Object Assembly	15.7	3.3	6	19	-1.63	2.97
ZVT 1-2-3_{45}	76.3	15.5	45	90	-1.01	-0.52
ZVT 179-177_{45}	35.1	9.5	14	49	-1.01	0.37
ZVT Z26-$Y25_{45}$	31.4	22.9	3	90	1.71	2.89
ZVT 1-2-3_{all}	56.7	18.8	39	114	2.00	4.29
ZVT 179-177_{all}	90.1	19.3	61	142	1.06	1.82
ZVT Z26-$Y25_{all}$	168.8	54.0	102	334	1.71	4.30
Grade (previous year)	3.9	0.6	3	5	0.04	-0.14
EPQ P	5.2	2.4	2	9	0.24	-1.30
EPQ E	17.7	4.6	9	22	-0.73	-0.98
EPQ N	14.6	5.2	6	23	-0.27	-0.99
EPQ L	5.2	2.7	0	10	-0.35	-0.07

Table 3

Descriptive Statistics for Psychometric Variables, Experiment 1, Lower Ability Group (N = 18)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	105.3	5.2	95.0	112	-0.57	-0.93
VIQ	105.8	9.3	90.0	120	-0.20	-1.18
Information	22.4	3.9	16.0	27	-0.42	-1.28
Comprehension	19.6	2.3	16.0	24	0.12	-0.82
Arithmetic	12.6	2.4	6.0	16	-1.45	2.61
Similarities	22.7	5.7	8.0	30	-1.48	2.12
Vocabulary	22.4	7.0	12.0	35	0.25	-0.77
PIQ	105.8	9.3	90.0	120	-0.20	-1.18
Digit Symbol	24.7	3.2	18.0	31	-0.17	0.42
Picture Completion	21.1	3.3	16.0	27	0.37	-0.77
Spatial	25.8	7.9	5.0	39	-0.91	1.66
Picture Arrangement	11.4	1.9	8.0	14	-0.50	-0.85
Object Assembly	12.6	3.9	7.0	18	0.01	-1.41
ZVT 1-2-3$_{45}$	66.4	11.2	47.0	89	0.14	-0.62
ZVT 179-177$_{45}$	22.8	9.5	4.0	37	-0.38	-0.79
ZVT Z26-Y25$_{45}$	14.4	6.0	4.0	24	0.08	-1.01
ZVT 1-2-3$_{all}$	60.4	9.8	45.0	82	0.79	0.50
ZVT 179-177$_{all}$	111.8	27.4	78.0	162	0.30	-1.39
ZVT Z26-Y25$_{all}$	285.3	88.8	165.0	480	0.57	-0.24
Grade (previous year)	3.2	0.5	2.0	4	0.16	0.18
EPQ P	6.3	3.5	2.0	15	0.93	0.56
EPQ E	15.1	5.5	3.0	22	-0.83	-0.13
EPQ N	15.3	5.4	3.0	23	-0.60	-0.02
EPQ L	5.9	4.1	1.0	14	0.78	-0.72

Table 4

Descriptive Statistics for Psychometric Variables, Experiment 2 (N = 24)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	114.0	9.0	96.0	132.0	-0.13	-0.28
VIQ	110.5	8.1	94.0	125.0	-0.26	-0.73
Information	24.2	3.9	15.0	32.0	-0.24	0.43
Comprehension	20.5	2.7	13.0	25.0	-1.02	1.32
Arithmetic	13.0	1.9	10.0	16.0	0.04	-1.30
Similarities	25.0	3.3	16.0	30.0	-0.66	0.71
Vocabulary	23.2	6.8	12.0	37.0	0.34	-0.62
PIQ	117.1	10.8	94.0	143.0	-0.08	0.65
Digit Symbol	26.3	3.2	19.0	33.0	-0.38	0.59
Picture Completion	22.5	4.2	13.0	33.0	0.13	1.21
Spatial	31.4	8.6	3.0	44.0	-1.89	4.76
Picture Arrangement	12.9	2.0	9.0	17.0	0.08	-0.63
Object Assembly	14.5	2.6	9.0	19.0	-0.02	-0.75
ZVT 1-2-3_{45}	65.1	16.9	4.0	89.0	-1.95	6.78
ZVT 179-177_{45}	29.5	12.1	8.0	59.0	0.16	0.14
ZVT Z26-$Y25_{45}$	21.3	7.7	9.0	37.0	0.36	-0.56
ZVT 1-2-3_{all}	60.7	13.6	44.0	89.0	0.57	-0.84
ZVT 179-177_{all}	106.5	35.9	65.0	182.0	0.50	-0.94
ZVT Z26-$Y25_{all}$	209.8	110.4	100.0	600.0	2.27	6.18
Grade (previous year)	3.7	0.8	2.0	5.0	-0.33	-0.08
EPQ P	5.7	3.0	1.0	11.0	0.10	-0.47
EPQ E	16.7	4.2	4.0	22.0	-1.30	2.23
EPQ N	12.3	4.9	0.0	19.0	-0.47	0.01
EPQ L	6.6	3.7	0.0	16.0	1.20	2.28

Table 5

Descriptive Statistics for Psychometric Variables, Experiment 2, Higher Ability Group (N = 24)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	121.1	5.1	116.0	132.0	1.00	0.29
VIQ	116.6	4.4	109.0	125.0	0.24	0.06
Information	26.1	3.4	21.0	32.0	0.19	-0.52
Comprehension	22.2	1.5	19.0	25.0	-0.15	1.20
Arithmetic	14.3	1.5	11.0	16.0	-0.91	0.48
Similarities	26.9	2.4	22.0	30.0	-0.89	-0.13
Vocabulary	27.6	5.7	20.0	37.0	0.20	-1.15
PIQ	124.2	6.7	118.0	143.0	2.25	5.99
Digit Symbol	27.7	1.9	24.0	30.0	-0.71	-0.15
Picture Completion	24.6	4.2	16.0	33.0	0.00	1.53
Spatial	35.7	4.5	28.0	44.0	0.06	-0.08
Picture Arrangement	13.3	2.4	9.0	17.0	-0.26	-0.49
Object Assembly	15.8	2.2	12.0	19.0	-0.25	-0.95
ZVT 1-2-3_{45}	71.3	8.4	59.0	89.0	0.65	0.31
ZVT 179-177_{45}	37.6	8.1	29.0	59.0	1.66	4.15
ZVT Z26-$Y25_{45}$	25.1	7.0	16.0	37.0	0.44	-1.29
ZVT 1-2-3_{all}	51.7	7.7	44.0	71.0	1.46	2.69
ZVT 179-177_{all}	84.0	22.1	65.0	142.0	1.79	3.77
ZVT Z26-$Y25_{all}$	157.6	38.2	100.0	227.0	0.07	-0.73
Grade (previous year)	3.7	1.1	2.0	5.0	-0.26	-1.00
EPQ P	5.5	3.3	1.0	11.0	0.00	-0.54
EPQ E	15.7	5.3	4.0	21.0	-1.02	0.67
EPQ N	10.9	5.7	0.0	19.0	-0.16	-0.41
EPQ L	6.2	3.5	3.0	16.0	2.19	5.69

Table 6

Descriptive Statistics for Psychometric Variables, Experiment 2, Lower Ability Group (N = 24)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	107.0	6.0	96.0	114.0	-0.52	-0.81
VIQ	104.3	6.1	94.0	114.0	0.15	-0.68
Information	22.3	3.5	15.0	26.0	-0.81	-0.04
Comprehension	18.8	2.7	13.0	22.0	-0.93	0.52
Arithmetic	11.8	1.4	10.0	15.0	0.98	1.22
Similarities	23.0	2.9	16.0	28.0	-0.94	2.64
Vocabulary	18.8	4.7	12.0	26.0	0.43	-0.82
PIQ	110.0	9.4	94.0	128.0	0.21	0.26
Digit Symbol	24.9	3.7	19.0	33.0	0.52	1.45
Picture Completion	20.5	3.1	13.0	24.0	-1.14	1.75
Spatial	27.1	9.8	3.0	35.0	-1.75	2.68
Picture Arrangement	12.5	1.7	10.0	15.0	0.28	-1.20
Object Assembly	13.2	2.5	9.0	18.0	0.54	0.59
ZVT 1-2-3_{45}	58.9	21.1	4.0	87.0	-1.47	4.05
ZVT 179-177_{45}	21.3	9.7	8.0	41.0	0.64	-0.14
ZVT Z26-$Y25_{45}$	17.5	6.5	9.0	29.0	0.50	-0.50
ZVT 1-2-3_{all}	69.7	12.4	47.0	89.0	-0.21	-0.67
ZVT 179-177_{all}	129.0	33.2	66.0	182.0	-0.43	0.02
ZVT Z26-$Y25_{all}$	262.0	134.5	146.0	600.0	1.60	2.77
Grade (previous year)	3.7	0.5	3.0	4.0	-0.81	-1.65
EPQ P	5.8	2.9	1.0	11.0	0.34	-0.07
EPQ E	17.8	2.7	14.0	22.0	0.02	-1.63
EPQ N	13.7	3.7	8.0	19.0	-0.03	-1.15
EPQ L	7.1	3.9	0.0	16.0	0.59	2.36

Table 7

Descriptive Statistics for Psychometric Variables. Combined Sample (N = 60)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	113.5	9.4	95.0	134.0	0.06	-0.50
VIQ	109.9	7.7	94.0	126.0	-0.14	-0.40
Information	23.9	4.1	15.0	33.0	0.10	-0.16
Comprehension	20.3	2.7	13.0	26.0	-0.27	-0.23
Arithmetic	13.3	2.1	6.0	17.0	-0.78	1.50
Similarities	24.9	4.2	8.0	31.0	-1.81	4.86
Vocabulary	23.2	6.9	11.0	38.0	0.32	-0.55
PIQ	116.4	12.3	90.0	143.0	-0.20	-0.37
Digit Symbol	26.8	3.6	18.0	34.0	-0.16	-0.01
Picture Completion	22.4	3.8	12.0	33.0	-0.25	0.64
Spatial	31.1	8.7	3.0	47.0	-1.07	1.82
Picture Arrangement	12.6	2.0	8.0	17.0	-0.25	-0.14
Object Assembly	14.3	3.4	6.0	19.0	-0.59	-0.48
ZVT 1-2-3_{45}	68.9	15.5	4.0	90.0	-1.14	3.51
ZVT 179-177_{45}	29.2	11.5	4.0	59.0	-0.14	-0.38
ZVT Z26-$Y25_{45}$	22.3	15.1	3.0	90.0	2.74	10.29
ZVT 1-2-3_{all}	59.4	14.3	39.0	114.0	1.29	2.28
ZVT 179-177_{all}	103.2	30.1	61.0	182.0	0.67	-0.51
ZVT Z26-$Y25_{all}$	220.2	100.0	100.0	600.0	1.52	2.75
Grade (previous year)	3.6	0.7	2.0	5.0	-0.03	-0.23
EPQ P	5.7	3.0	1.0	15.0	0.59	0.31
EPQ E	16.5	4.8	3.0	22.0	-0.96	0.42
EPQ N	13.9	5.3	0.0	23.0	-0.33	-0.46
EPQ L	6.0	3.5	0.0	16.0	0.85	0.99

Table 8

Descriptive Statistics for Psychometric Variables. Combined Sample. Higher Ability Group (N = 30)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	121.0	5.7	114.0	134.0	0.73	-0.23
VIQ	115.2	5.2	106.0	126.0	0.28	-0.53
Information	25.3	4.0	20.0	33.0	0.48	-0.97
Comprehension	21.2	2.7	15.0	26.0	-0.49	-0.19
Arithmetic	14.2	1.6	11.0	17.0	-0.19	-0.68
Similarities	27.0	2.2	22.0	31.0	-0.51	-0.31
Vocabulary	25.4	6.8	11.0	38.0	0.14	-0.41
PIQ	125.2	7.5	107.0	143.0	0.45	1.00
Digit Symbol	28.7	2.6	24.0	34.0	0.23	-0.29
Picture Completion	23.9	3.9	12.0	33.0	-0.86	2.90
Spatial	35.8	5.7	25.0	47.0	-0.36	-0.31
Picture Arrangement	13.3	1.8	9.0	17.0	-0.22	0.01
Object Assembly	15.7	2.9	6.0	19.0	-1.46	2.96
ZVT 1-2-3$_{45}$	74.3	13.2	45.0	90.0	-0.58	-0.66
ZVT 179-177$_{45}$	36.1	8.9	14.0	59.0	-0.33	1.59
ZVT Z26-Y25$_{45}$	28.9	18.3	3.0	90.0	2.23	6.01
ZVT 1-2-3$_{all}$	54.7	15.4	39.0	114.0	2.42	7.07
ZVT 179-177$_{all}$	87.6	20.3	61.0	142.0	1.23	1.64
ZVT Z26-Y25$_{all}$	164.3	47.9	100.0	334.0	1.50	4.16
Grade (previous year)	3.8	0.8	2.0	5.0	-0.43	-0.08
EPQ P	5.3	2.7	1.0	11.0	0.14	-0.65
EPQ E	16.9	4.9	4.0	22.0	-0.86	-0.02
EPQ N	13.1	5.6	0.0	23.0	-0.25	-0.66
EPQ L	5.6	3.1	0.0	16.0	1.11	3.73

Table 9

Descriptive Statistics for Psychometric Variables, Combined Sample, Lower Ability Group (N = 30)

Measure	Mean	SD	Min.	Max.	Skewness	Kurtosis
FIQ	106.0	5.5	95.0	114.0	-0.45	-0.89
VIQ	104.6	5.9	94.0	114.0	-0.14	-0.80
Information	22.4	3.7	15.0	27.0	-0.51	-0.97
Comprehension	19.3	2.4	13.0	24.0	-0.44	0.12
Arithmetic	12.3	2.1	6.0	16.0	-0.88	1.77
Similarities	22.8	4.7	8.0	30.0	-1.58	3.24
Vocabulary	21.0	6.4	12.0	35.0	0.53	-0.40
PIQ	107.5	9.4	90.0	128.0	-0.03	-0.50
Digit Symbol	24.8	3.3	18.0	33.0	0.17	0.64
Picture Completion	20.8	3.2	13.0	27.0	-0.11	0.05
Spatial	26.3	8.6	3.0	39.0	-1.23	1.45
Picture Arrangement	11.9	1.9	8.0	15.0	-0.33	-0.39
Object Assembly	12.8	3.4	7.0	18.0	-0.03	-0.89
ZVT 1-2-3$_{45}$	63.4	16.0	4.0	89.0	-1.54	5.54
ZVT 179-177$_{45}$	22.2	9.5	4.0	41.0	0.02	-0.83
ZVT Z26-Y25$_{45}$	15.6	6.3	4.0	29.0	0.28	-0.51
ZVT 1-2-3$_{all}$	64.1	11.6	45.0	89.0	0.44	-0.65
ZVT 179-177$_{all}$	118.7	30.5	66.0	182.0	0.09	-0.93
ZVT Z26-Y25$_{all}$	276.0	107.8	146.0	600.0	1.10	1.43
Grade (previous year)	3.4	0.6	2.0	4.0	-0.20	-0.84
EPQ P	6.1	3.2	1.0	15.0	0.80	0.48
EPQ E	16.2	4.7	3.0	22.0	-1.17	1.17
EPQ N	14.7	4.8	3.0	23.0	-0.30	-0.23
EPQ L	6.4	4.0	0.0	16.0	0.63	-0.11

Table 10

Correlations between Ability Measures and Percent Correct Detections (N = 60)

	SOA		
	150	50	25
FIQ	.42 **	.31 *	.43 **
VIQ	.32 *	.36 **	.30 *
Information	.33 *	.28 *	.22
Comprehension	.26 *	.29 *	.19 *
Arithmetic	.31 *	.39 **	.34 **
Similarities	.00	.11	.14
Vocabulary	.11	.20	.22
PIQ	.41 **	.19	.42 **
Digit Symbol	.30 *	.23	.46 **
Picture Completion	.28 *	.07	.23
Spatial	.16	.12	.28 *
Picture Arrangement	.33 **	-.03	.22
Object Assembly	.30 *	.21	.29 *
ZVT 1-2-3_{45}	.14	.26 *	.29 *
ZVT 179-177_{45}	.17	.18	.22
ZVT Z26-$Y25_{45}$	.28 *	.21	.27 *
ZVT 1-2-3_{all}	-.14	-.20	-.44 **
ZVT 179-177_{all}	-.16	-.12	-.11
ZVT Z26-$Y25_{all}$	-.18	-.18	-.27 *
Grade (previous year)	.14	.01	.08

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

Table 11

Correlations between Ability Measures and Number of False Positives (N = 60)

	SOA		
	150	50	25
FIQ			
VIQ	-.19	-.12	-.05
Information	-.07	-.03	-.04
Comprehension	-.10	-.11	.02
Arithmetic	-.22	-.15	-.13
Similarities	-.18	-.12	-.15
Vocabulary	.00	.03	-.01
PIQ	-.33 *	-.02	-.08
Digit Symbol	-.23	-.07	-.13
Picture Completion	-.17	-.08	-.03
Spatial	-.30 *	-.04	-.10
Picture Arrangement	-.17	.14	.09
Object Assembly	-.25	-.06	-.16
ZVT 1-2-3_{45}	-.31 *	-.22	-.17
ZVT 179-177_{45}	-.25	-.14	-.03
ZVT Z26-$Y25_{45}$	-.22	-.14	-.17
ZVT 1-2-3_{all}	.34 **	.19	.10
ZVT 179-177_{all}	.14	.10	-.02
ZVT Z26-$Y25_{all}$	.21	.01	.03
Grade (previous year)	-.08	.07	.07

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

Table 12

Correlations between Ability Measures and RT (N = 60)

	SOA		
	150	50	25
FIQ	-.44 **	-.45 **	-.27 *
VIQ	-.39 **	-.42 **	-.19
Information	-.38 **	-.35 **	-.20
Comprehension	-.34 **	-.28 *	-.25
Arithmetic	-.34 **	-.28 *	-.19
Similarities	-.32 *	-.29 *	-.16
Vocabulary	-.10	-.07	.00
PIQ	-.36 **	-.36 **	-.26 *
Digit Symbol	-.44 **	-.41 **	-.26 *
Picture Completion	-.09	.06	.01
Spatial	-.35 **	-.27 *	-.28 *
Picture Arrangement	-.18	-.25	-.23
Object Assembly	-.16	-.27 *	-.08
ZVT 1-2-3_{45}	-.31 *	-.28 *	-.30 *
ZVT 179-177_{45}	-.23	-.27 *	-.23
ZVT Z26-$Y25_{45}$	-.40 **	-.39 **	-.27 *
ZVT 1-2-3_{all}	.22	.30 *	.21
ZVT 179-177_{all}	.17	.19	.14
ZVT Z26-$Y25_{all}$	.34 **	.52 **	.21
Grade (previous year)	-.13	-.25	-.21

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

Table 13

Correlations between Ability Measures and SDrt (N = 60)

	SOA		
	150	50	25
FIQ	-.54 **	-.39 **	-.38 **
VIQ	-.48 **	-.38 **	-.31 *
Information	-.34 **	-.23	-.20
Comprehension	-.36 **	-.22	-.27 *
Arithmetic	-.42 **	-.36 **	-.30 *
Similarities	-.30 *	-.15	-.16
Vocabulary	-.05	-.09	.05
PIQ	-.47 **	-.32 *	-.36 **
Digit Symbol	-.47 **	-.27 *	-.25
Picture Completion	-.08	-.02	-.15
Spatial	-.42 **	-.19	-.30 *
Picture Arrangement	-.20	-.28 *	-.20
Object Assembly	-.26 *	-.30 *	-.25
ZVT 1-2-3$_{45}$	-.39 **	-.37 **	-.35 **
ZVT 179-177$_{45}$	-.26 *	-.30 *	-.31 *
ZVT Z26-Y25$_{45}$	-.42 **	-.26 *	-.27 *
ZVT 1-2-3$_{all}$	.29 *	.26 *	.35 **
ZVT 179-177$_{all}$	.18	.10	.12
ZVT Z26-Y25$_{all}$	.48 **	.38 **	.34 **
Grade (previous year)	-.10	-.26 *	-.14

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

Table 14

Correlations between Ability Measures and P3 Latency (N = 60)

	SOA		
	150	50	25
FIQ	-.13	-.28 *	-.45 **
VIQ	-.13	-.13	-.21
Information	-.01	.04	.03
Comprehension	.02	-.02	.05
Arithmetic	-.28 *	-.21	-.23
Similarities	-.02	-.15	-.23
Vocabulary	.11	.05	.01
PIQ	-.14	-.37 **	-.56 **
Digit Symbol	-.05	-.30 *	-.49 **
Picture Completion	.16	-.08	-.13
Spatial	-.15	-.34 **	-.40 **
Picture Arrangement	-.14	-.21	-.16
Object Assembly	-.05	-.26 *	-.62 **
ZVT 1-2-3_{45}	.07	-.17	-.38 **
ZVT 179-177_{45}	-.14	-.27 *	-.23
ZVT Z26-$Y25_{45}$	.00	-.02	-.29 *
ZVT 1-2-3_{all}	-.09	.01	-.29 *
ZVT 179-177_{all}	.05	.23	.20
ZVT Z26-$Y25_{all}$	-.11	-.05	.08
Grade (previous year)	.16	.20	.24

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

Table 15

Correlations between Ability Measures and P3 Amplitude (N = 60)

	SOA		
	150	50	25
FIQ	.34 **	.41 **	.36 **
VIQ	.28 *	.35 **	.39 **
Information	.03	.10	.13
Comprehension	.19	.30 *	.35 **
Arithmetic	.27 *	.36 **	.47 **
Similarities	.16	.15	.14
Vocabulary	-.01	.05	.04
PIQ	.35 **	.40 **	.29 *
Digit Symbol	.24	.32 *	.20
Picture Completion	.11	.15	.08
Spatial	.19	.21	.17
Picture Arrangement	.29 *	.29 *	.24
Object Assembly	.24	.30 *	.18
ZVT 1-2-3_{45}	.36 **	.31 *	.22
ZVT 179-177_{45}	.31 *	.33 *	.35 **
ZVT Z26-$Y25_{45}$	.25	.18	.16
ZVT 1-2-3_{all}	-.29 *	-.35 **	-.34 **
ZVT 179-177_{all}	-.36 *	-.39 *	-.36 *
ZVT Z26-$Y25_{all}$	-.30 *	-.29 *	-.30 *
Grade (previous year)	.32 *	.27 *	.21

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

Table 16

Correlations between Ability Measures and MMN Latency (N = 60)

	SOA		
	150	50	25
FIQ	-.14	-.15	-.35 **
VIQ	-.10	-.11	-.22
Information	-.08	.00	-.24
Comprehension	-.06	-.06	-.07
Arithmetic	-.13	-.25	-.11
Similarities	-.08	-.28 *	-.13
Vocabulary	-.05	-.23	-.23
PIQ	-.14	-.15	-.36 **
Digit Symbol	-.06	-.34 *	-.23
Picture Completion	.00	-.20	-.40 **
Spatial	-.04	-.06	-.30 *
Picture Arrangement	-.13	.00	-.21
Object Assembly	-.20	-.16	-.18
ZVT 1-2-3_{45}	-.02	-.01	-.06
ZVT 179-177_{45}	-.10	.03	-.35 **
ZVT Z26-$Y25_{45}$	.06	-.21	-.23
ZVT 1-2-3_{all}	.04	.18	.16
ZVT 179-177_{all}	-.03	-.02	.27 *
ZVT Z26-$Y25_{all}$	.01	.10	.32 *
Grade (previous year)	.07	-.01	-.14

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

Table 17

Correlations between Ability Measures and MMN Amplitude (N = 60)

	SOA		
	150	50	25
FIQ	-.01	-.24	-.31 *
VIQ	.02	-.26 *	-.30 *
Information	.12	-.21	-.21
Comprehension	.13	-.24	-.16
Arithmetic	-.01	-.24	-.23
Similarities	-.10	-.09	-.11
Vocabulary	.15	-.15	-.04
PIQ	.02	-.17	-.25
Digit Symbol	-.09	-.21	-.28 *
Picture Completion	.19	.00	-.27 *
Spatial	-.09	-.20	.02
Picture Arrangement	-.04	-.04	-.20
Object Assembly	.23	-.08	-.13
ZVT 1-2-3_{45}	-.18	-.13	-.10
ZVT 179-177_{45}	.12	-.19	-.17
ZVT Z26-$Y25_{45}$	.24	-.11	-.25
ZVT 1-2-3_{all}	.05	.12	.16
ZVT 179-177_{all}	-.14	.14	.21
ZVT Z26-$Y25_{all}$	.06	.13	.31 *
Grade (previous year)	-.05	-.02	-.32 *

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

Table 18

Reliabilities, Corrected and Uncorrected g-factor Loadings and Rankings for Mental Ability Subtests, Corrected and Uncorrected Correlations and Rankings of P3 Amplitude with Mental Ability Subtests for Vector Analysis

		g factor loading				P3 amplitude correlations			
		uncorrected		corrected		uncorrected		corrected	
		A	B	C	D	E	F	G	H
Subtest	rel.	*g*	rank	*g'*	rank'	r	rank	r'	rank'
$179\text{-}177_{45}$	.81	.7973	17	.8859	17	.3206	16	.3563	16
$179\text{-}177_{all}$	.91	.6710	16	.7034	14	.3174	15	.3327	13
Similar	.90	.6642	15	.7001	13	.1849	4	.1950	4
$Z26\text{-}Y25_{all}$	.83	.6640	14	.7288	16	.3153	14	.3461	15
Spatial	.96	.6602	13	.6738	12	.2759	9	.2816	9
Digit	.95	.6537	12	.6706	11	.2703	8	.2774	8
$Z26\text{-}Y25_{45}$	.80	.6352	11	.7102	15	.1913	5	.2140	5
Arithmetic	.80	.5506	10	.6156	10	.2996	12	.3350	14
$1\text{-}2\text{-}3_{all}$	.90	.5480	9	.5778	9	.3954	17	.4253	17
Compre	.88	.5391	8	.5747	8	.2553	7	.2722	7
Object	.89	.5014	7	.5315	6	.3003	13	.3184	10
Pictcomp	.88	.4991	6	.5320	7	.0539	3	.0574	3
Vocab	.88	.4877	5	.5199	4	.0265	2	.0282	2
Pictarr	.85	.4857	4	.5268	5	.2987	11	.3241	12
$1\text{-}2\text{-}3_{45}$	.86	.4651	3	.5015	3	.2968	10	.3200	11
Inform	.87	.4098	2	.4394	2	.0177	1	.0190	1
Grade	.87	.3470	1	.3720	1	.2174	6	.2331	6

Note. Similar: similarities; Digit: digit symbol; Compre: comprehension; Object: object assembly; Pictcomp: picture completion; Vocab: vocabulary; Pictarr: picture arrangement; Inform: information. rel.: reliability coefficient of mental ability subtests; A: subtests' uncorrected g loadings; B: subtests' uncorrected rank ordering; C: subtests' corrected g loadings; D: subtests' corrected rank ordering; E: subtest's uncorrected correlation with P3 amplitude; F: rank ordering of subtests' uncorrected correlation with P3 amplitude; G: subtests' corrected correlation with P3 amplitude; H: rank ordering of subtests' corrected correlation with P3 amplitude.

Table 19

Correlations and Probabilities for Vector Analysis of P3 and MMN Latencies and Amplitudes

	r_{AE}	p	r_{BF}	p	r_{CG}	p	r_{DH}	p
ERP Measures – Active								
P3 Latency	.12	.32	.07	.40	.10	.35	.04	.44
P3 Amplitude	.41	.05	.41	*	.46	.05	.44	*
ERP Measures – Passive								
MMN Latency	.38	.07	.32	.11	.38	.07	.28	.14
MMN Amplitude	.05	.42	.07	.40	.07	.39	.05	.42

Note. r_{AE}: Pearson correlation between subtests' uncorrected g loadings and correlation with P3 amplitude: r_{BF}: Spearman rank-order correlation between rank ordering of subtests' uncorrected g loadings and correlation with P3 amplitude: r_{CG}: Pearson correlation between subtests' corrected g loadings and correlation with P3 amplitude: r_{DH}: Spearman rank order correlation between rank ordering of subtests g loadings and correlation with P3 amplitude

* $p < .05$.

Figure 1

Scatterplot of Correlation of P3 Amplitude with Mental Ability Subtests Plotted as a Function of the Subtests' g Loading

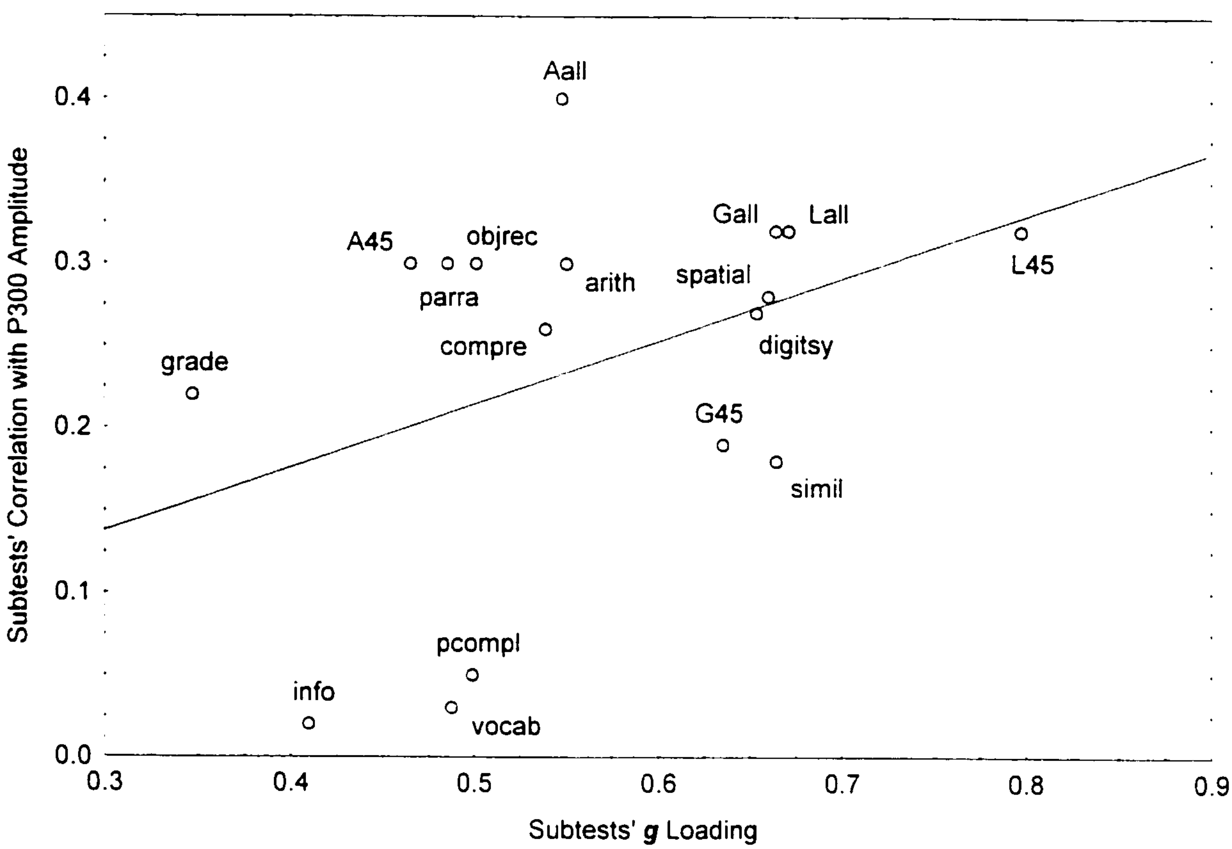

Table 20

Hierarchical Factor Analysis of Ability, Performance, and ERP Measures (N = 60)

	Secondary Factor	Primary Factors				
		1	2	3	4	5
Grade	0.18	-.04	**.51**	**.37**	-.06	.24
Information	0.33	-.08	.08	-.06	**.59**	.01
Comprehension	0.51	-.17	-.19	**.30**	**.55**	.00
Arithmetic	0.53	**.50**	**-.33**	.08	.20	.00
Similarities	0.53	.03	.09	-.21	**.30**	**-.42**
Vocabulary	0.43	.09	.03	-.04	**.72**	.13
Digit Symbol	0.48	**.65**	-.10	.01	-.21	-.13
Pictcomp	0.46	.19	-.01	**.50**	.03	.19
Spatial	0.57	**.38**	.28	-.05	-.06	-.25
Pictarr	0.52	-.10	-.06	**.38**	.03	-.19
Object Assembly	0.38	**.50**	.08	**.33**	-.12	.26
ZVT 45	0.69	.07	-.05	.20	-.08	**-.45**
ZVT complete	-0.59	-.07	-.16	.00	.06	**.48**
PCR	-0.24	.11	**-.69**	.18	-.04	.26
RT	0.20	-.02	**.88**	-.04	.11	.07
SDrt	0.21	-.03	**.87**	-.02	-.11	-.07
P3 latency	-0.27	**-.62**	-.01	.17	.08	.00
MMN latency	-0.37	**-.62**	.06	.22	**-.32**	-.11
P3 amplitude	0.46	-.21	-.03	**.59**	-.07	-.09
MMN amplitude	-0.26	.09	.04	.08	.08	**.43**
% total	38.3	25.1	13.2	9.0	7.6	6.8
cumulative %	38.3	63.4	76.6	85.6	93.2	100.0

Note. Digit: digit symbol: Pictcomp: picture completion: Pictarr: picture arrangement: ZVT 45: composite of ZVT scores from the 45 second administration across each SOA: ZVT complete: composite of ZVT scores from the time-to-complete administration across each SOA: PCR: composite of percent correct responses across SOA: RT: composite of reaction time across SOA: SDrt: composite of standard deviation of reaction time for each individual across SOA: P3 latency: composite of P3 latencies across SOA: MMN latency: composite of MMN latencies across SOA: P3 amplitude: composite of P3 amplitudes across SOA: MMN amplitude: composite of MMN amplitudes across SOA: % total: percentage of total variance accounted for by the secondary factor and each primary factor.

Note. Correlations between oblique factors (clusters of variables with unique loadings):

	1	2	3	4	5
1	1	0.09	0.38	0.30	0.50
2	0.09	1	0.18	0.12	0.26
3	0.38	0.18	1	0.46	0.53
4	0.30	0.12	0.46	1	0.40
5	0.50	0.26	0.53	0.40	1