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Prior research has suggested that brain recordings such as the neuroelectric evoked potential (EP) and neuromagnetic fields may substantially augment personnel assessment procedures. Such procedures include the measurement and prediction of on-job performance.

Areas covered in this report include a discussion of individual difference measurement and its history, followed by a description of evidence for the relationship between neuroelectric recordings and aptitude. Emphasis is given to relationships between EP recordings and on-job performance assessment that this Center found over the last 12 years. Finally, a discussion follows of new techniques that we and others are examining and developing to improve the sensitivity of brain function measures, using the neuromagnetic evoked field (EF). Relationships between the EF and on-job performance are described.

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Evoked Brain Activity and Personnel Performance

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Evoked Brain Activity and Personnel Performance

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San Diego, California 92152-6800

FOREWORD

This report is a general review article dealing with historical aspects, rationale, and research results relating brain activity to performance. Emphasis is on describing related research that has taken place at the Navy Personnel Research and Development Center over the past several years.

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Captain, U.S. Navy
Commanding Officer

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Technical Director

SUMMARY

Prior research has suggested that brain recordings such as the neuroelectric evoked potential (EP) and neuromagnetic fields may substantially augment personnel assessment procedures. Such procedures include the measurement and prediction of on-job performance.

Areas covered in this report include a discussion of individual difference measurement and its history, followed by a description of evidence for the relationship between neuroelectric recordings and aptitude. Emphasis is given to relationships between EP recordings and on-job performance assessment that this Center found over the last 12 years. Finally, a discussion follows of new techniques that we and others are examining and developing to improve the sensitivity of brain function measures, using the neuromagnetic evoked field (EF). Relationships between the EF and on-job performance are described.

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INTRODUCTION

The primary thrust of the neuroscience research program at the Navy Personnel Research and Development Center (NPRDC) is to develop a technology for measuring evoked brain activity that correlates with the performance of military personnel and serves as a predictor of that performance. NPRDC has been investigating neuroelectric and neuromagnetic recordings to assess individual differences in brain processing and their relationships to on-job performance. Neuroelectric recordings include electroencephalography (EEG) and the evoked potential (EP), while neuromagnetic recordings involve magnetoencephalography (MEG) and evoked fields (EF). The EEG (measured in microvolts) and MEG (measured in femtotesla) show minute ongoing brain activity. The EP and EF show the brain response averaged over several trials which result from precisely recorded visual or auditory stimulation. Neuroscience research has significantly advanced the understanding of brain function during the last several years. Such advances have been due to developments in electronics and computer technology as well as to progress in experimental procedures and data analytic tools.

It is our objective here to present a brief discussion of individual difference measurement and its history, and then to present evidence for the relationship between neuroelectric recordings and aptitude. We will emphasize the relationships between EP and on-job performance assessment that we have found over the last dozen or so years, and conclude with a brief discussion of new techniques that we and others are examining and developing to improve the sensitivity of brain function measures, using the neuromagnetic evoked field.

INDIVIDUAL DIFFERENCE MEASUREMENT

An Historic View of Psychological Testing

Dahlstrom (1985) provides an interesting review of developments in psychological testing that gives historical relevance to our current research in the use of neuroscience procedures for personnel assessment. He suggests that some of the earliest forms of testing were done by the Chinese between 2200 B.C. and 1905 A.D. The early Chinese testing covered not only writing ability in composing poetry and prose, but also the ability to reference important and wide-ranging topics of law, finance, agriculture, etc. Job sample tests were used to demonstrate abilities related to music, archery, horsemanship, and arithmetic (Buss & Poley, 1976). Dahlstrom claims the early personnel selection testing by the U.S., German, and British governments had roots in the early Chinese testing procedures. Other testing by Western governments, however, focused on more physical aspects of the subjects being tested, which included anatomy and physiology. Such focus can probably be traced to the Classical Greeks, i.e., Aristotle, Plato, Pythagoras, Hippocrates, and Galen. The Greeks suggested relationships between physiognomy (attributes related to physical features), anatomy and physiology, and the person's character and ability. Dahlstrom states that "These authorities gave convincing rationales and explanations for individual differences in intellective insights, wisdom and judgment, emotional control, amiability and tolerance, as well as dispositions to depression, fearfulness, and psychosis" (p. 65).

Other relationships between body states and temperament and emotionality were suggested by de la Chambre (France) and Huarte (Spain) during the 1500s and 1600s. Dahlstrom (1985, p. 65) continues noting that Huarte devised an elaborate explanation of differences between individuals ". . . based upon hypothesized internal states like those employed by de la Chambre, as well as on body build and physiognomic features, and covered intellective, tempermental, and characterological attributes. Huarte not only provided specific means of character reading but prescribed methods for training and enhancing basic talents and capacities. This work met with great interest and wide acceptance, reflecting less the validity of his methods than the need for some means of dealing with and understanding human differences." Phrenology developed as a result of the interest in explaining behavior shifting from internal functions of the body to the brain. Even though phrenology proved ineffective as an assessment tool, it did provide a stimulus for further, more productive work in physiological psychology based on the conviction that the brain was the "organ of the mind," a phrase used by Gall, the German proponent of phrenology. Phrenology also contributed the important concept of localization of specific functions within the brain (Boring, 1950).

Measurement of mental abilities was first undertaken by Binet (France) and Galton (England), with Binet being the first to develop a practical psychometric instrument. Further refinement of ability testing came about when chronological age and mental age were used to compute a measure of intelligence (IQ = mental/chronological age), and through test standardization, statistical reliability/validity, and factor and other statistical analyses.

Testing of military personnel received impetus during World War I with the development of the Army Alpha Test (verbal) and the Army Beta Test (non-verbal). Again, Dahlstrom (1985) provides interesting reading concerning the development of the Army Alpha and Beta tests as well as the research performed on these test instruments (i.e., effects of fatigue on test scores, interrelationships of subtests for various groups and individuals). Numerous tests were developed before, during, and after World War II by Yerkes, Thorndike, Cattell, Wechsler, Seashore, Strong, and others. College aptitude tests and the MMPI and other personality tests were developed along with tests designed for military purposes. The latter include the Armed Forces Qualification Test (AFQT), Armed Services Vocational Aptitude Battery (ASVAB), and others specific to the Navy. The Navy Basic Test Battery (BTB) subtests for military personnel assessment include the General Classification Test (GCT), the Arithmetic Reasoning Inventory (ARI), the Mechanical Aptitude Test (MECH), and the Electronics Technical Selection Test (ETST). The ASVAB replaced the BTB in 1976 for use in selecting and assigning Navy recruits.

Uses of Tests

There are now a multitude of test instruments and procedures. The Ninth Mental Measurements Yearbook lists in excess of 1400 tests that provide scores on over 6000 variables (Mitchell, 1985).

Psychological measurement instruments can be clustered in terms of the degree to which responses to items can be judged correct or incorrect. If there is no correct response, the test may be considered to be non-cognitive. Non-cognitive tests include those that measure personality, interests, values, beliefs, and attitudes. In short, the non-cognitive tests tap the subjects' model of the real world and how they feel about elements therein. If the responses can be judged "right" or "wrong," the test is spoken of as a cognitive test. Cognitive tests measure achievement, abilities, and aptitudes. The items in the various types of cognitive tests may be very similar; the distinction is made in terms of the use of the test.

Achievement tests measure past performance--particularly learning performance. Achievement measures are valid in the sense of content validity. A particular domain of skills and knowledge must be identified and items prepared which sample that domain. The achievement measure is valid to the extent that the items are properly prepared and the domain is adequately sampled, usually as judged by subject matter experts.

Ability tests usually measure present performance. They are properly validated in the sense of construct validity. A measure of a particular ability is correlated with other ability measures. If the measure is highly correlated with other measures of the same ability and uncorrelated with measures of other abilities, then one can conclude that the ability measure is valid.

Aptitude tests are related to future performance. They are used to predict future job and educational performance, and are validated in terms of criterion validation--either predictive or concurrent. An aptitude test is considered valid to the extent its scores relate to criterion behavior, such as performance in a particular course or on a specific job task. Ideally the test is administered to a representative sample of those to be considered for selection (i.e., predictive validation). A less advisable approach is to study the relationship between the predicting test and criterion behavior in those already selected and performing the activity (i.e., concurrent validation). The problem with concurrent validation is that the sample does not represent a group from which selection will eventually be made--selection by some means has already occurred--and the experience of performing the criterion behavior has conceivably changed the individuals. The individuals perform differently on the test because of the experiences of course instruction or task performance. Traditionally, the degree of validity is expressed in terms of correlation coefficients between the aptitude measure and the criterion measure. Contingency tables showing success rate or average performance for differing intervals of the aptitude score are generally more informative.

Most cognitive measurement techniques depend on an evaluation of the products of cognition. We compare the answers to questions against a standard. An alternative is to measure the cognitive processes rather than their products. For instance, in the past, attention has been given to the measurement of eye movements (Dillon & Wisher, 1981), reaction latency (Jensen, 1985; Larson & Saccuzzo, 1986) and inspection time (Saccuzzo, Larson & Rimland, 1986). The approach we are reporting on, however, can be characterized as process measurement of aptitudes and involves both predictive and concurrent validation.

Individuals differ in their ability to adapt to training and job demands. Such adaptability depends on factors such as basic aptitude and the ability to tolerate new and stressful situations.

Traditional personnel assessment in both military and civilian communities has depended heavily on paper-and-pencil tests that predict school and training performance fairly well, but do not predict on-job performance with the same degree of accuracy. Linn (1982, after Ghiselli, 1966) examined relationships between aptitude test scores and training and proficiency criteria. Validity coefficients averaged between 0.30 and 0.40 for training criteria and less than 0.20 for proficiency criteria. For example, with training criteria, they found validity coefficients of 0.47 for clerks, 0.35 for protective services (fire, police), 0.54 for personal services (hospital attendants), 0.15 for vehicle operators, 0.41 for trades and crafts, and 0.40 for industrial workers. Validity coefficients of aptitude test scores with proficiency criteria for these same groups were 0.27, 0.23, 0.03, 0.14, 0.19, and 0.16.

An extensive literature review on predicting military job performance was published by Vineberg and Joyner (1982). This review covered the years 1952-1982. They found aptitude variable correlations of about 0.40 for job knowledge, 0.10 to 0.35 for job sample tests, 0.24 for composite measures of suitability, and 0.15 for global ratings of performance. Hunter and Hunter (1984) found that cognitive tests correlated with on-the-job performance in the low to moderate range depending on the complexity of the information-processing requirements of the job. For certain highly skilled people, such as aviators and sonar operators, training attrition is still too high. We must explore new techniques for predicting performance and selecting personnel.

The introduction of computer adaptive testing (CAT), based on item response theory and adaptive testing algorithms, has allowed more reliable measurement of personnel at all ability levels. Although CAT provides the potential for some improvement in personnel assessment, it remains to be demonstrated whether CAT will be able to adequately predict on-job performance. Its impact is likely to be more in the realm of spatial-visual reasoning, memory, and attention than in the measuring of verbal intelligence or psychomotor abilities (Hunt & Pellegrino, 1985). The applications of CAT in large-scale selection testing are currently being explored at NPRDC. Other new approaches involve the measurement of cognitive processes rather than the products of cognition.

To improve aptitude measurement and prediction of on-job performance and attrition, new testing procedures are required to supplement the information from existing tests. Neuroscience procedures (e.g., neuroelectric and neuromagnetic recordings) that measure brain processes have shown promise for improved performance prediction (Lewis, 1983a; Lewis, Trejo, Blackburn, & Blankenship, 1986). Researchers have demonstrated that such procedures generate reliable measures useful in discriminating normal populations from populations with cognitive dysfunctions and disorders (John, Prichep, Ahn, Easton, Fridman, & Kaye, 1983). It is hoped that assessing brain information will facilitate more accurate prediction of performance under training, nonstressed (baseline), fatigue, and stressful on-job performance conditions.

NEUROELECTRIC MEASURES OF BRAIN ACTIVITY

EEG/EP Individuality and Test-Retest Reliability

Neuroelectric or neuromagnetic measures for personnel assessment must be sensitive to individual differences and show long-term stability or reliability. Stability refers to the similarity in the waveforms of an individual across time. Stability over time is a prerequisite for using neuroelectric data for personnel assessment and has been demonstrated in this and other laboratories (Lewis, 1984). The usual procedure for determining stability involves computing the correlation coefficient between two waveforms (Glaser & Ruchkin, 1976). High correlation suggests stability, while low correlation suggests variability.

Early papers by Travis and Gottlober (1936, 1937), Davis and Davis (1936), Rubin (1938) and Williams (1939) suggested that EEG activity showed individuality and was stable from day to day. Such activity patterns were shown to be not only stable and individualistic, but also inherited (Lennox, Gibbs, & Gibbs, 1945). More recently, several studies have found stable EEG records within subjects (Fein, Galin, Johnstone, Yingling, Marcus, & Kiersch, 1983; Matousek, Arvidsson, & Friberg, 1979; Stassen, 1980; Van Dis, Corner, Dapper, Hanewald, & Kok, 1979). Research has also demonstrated that EEG and stimulus-locked EEG records (EP) are very sensitive to individual differences (Berkhout & Walter, 1968; Brazier, 1962; Buchsbaum & Pfefferbaum, 1971; Callaway, 1975; Henry, 1941a, b; Lewis, 1983a; Uttal & Cook, 1964; Werre & Smith, 1964). Early research relating more variable, state-like attributes (e.g., anxiety arousal) to psychological aspects were described by Travis (1937), Travis and Egan (1938), Hoagland, Cameron, Rubin, and Tegelberg (1938), Knott (1938), and Hadley (1940, 1941).

With the advent of improved instrumentation and signal averaging techniques, tighter stimulus-response observations have become possible in neuroscience research. Sensory systems (i.e., visual, auditory, somatosensory) as well as higher order cognitive processing and psychological variables can now be explored in greater detail and with greater precision. However, much variability in EP recordings has been noted between and within subjects. EP variability, its contributing factors, and its relationship to cognitive variability have been discussed by Callaway (1975). Greater EP variability has been noted in patients with mental and behavioral disorders (Buchsbaum & Coppola, 1977; Callaway, 1975; Callaway, Jones, & Donchin, 1970; Cohen, 1972; Shagass, 1972) and in newborn infants (Ellingson, 1970) but not in normal adults. Dustman and Beck (1969) reported the stabilizing of visual EP amplitude with maturity at about age 16. Ellingson, Lathrop, Danahy, and Nelson (1973), studying adults and infants, found greater visual EP stability within sessions than over days; and adults showed greater stability than did the infants. These authors used the Pearson product-moment correlation on the 500 msec visual EP (128 data points) for their stability measure.

Test-retest correlations for the EP have been reported to range from about 0.70 to 0.90 for varying modalities (visual, auditory, somatosensory), subject age groups, and measures (amplitude, latency, slopes). Stability of evoked activity has been examined for the visual modality (Dustman & Beck, 1963; Kooi & Bagchi, 1964; Wicke, Donchin, & Lindsley, 1964); the auditory modality (Buchsbaum, Henkin, & Christiansen, 1974; Ellingson, Danahy, Nelson, & Lathrop, 1974); and by comparing visual and auditory modalities (Buchsbaum & Coppola, 1977). Results have shown high within-subject and low between-subject stability. For the visual modality, greatest stability has been found in the occipital and central regions (Kooi & Bagchi, 1964). Auditory EP stability has been greatest for children (6-9 years) and least for older adults (40-60 years) (Buchsbaum et al., 1974). Comparison of visual and auditory records showed greater stability for the visual than for the auditory modality (Buchsbaum & Coppola, 1977). Their area-under-curve measures showed greater stability than baseline-to-peak measures for records obtained 2 or more weeks apart.

In a recent study (Lewis, 1984), visual, auditory, and bimodal (visual plus auditory) EP records were obtained about 2 hours apart from a group (N = 8) of young adult males. Their ages averaged 19.6 +/- 0.9 years (range: 19-21). Similar records were obtained about 2 months apart from a group of older adults (N = 7 males, 1 female). Ages for this group averaged 33.1 +/- 9.6 years (range: 21-43). Waveform stability was assessed using a cross-correlation measure, similar to that used by Glaser and Ruchkin (1976). No statistically significant EP amplitude or temporal stability differences were found between the two groups. Age, however, was positively correlated with visual EP stability measures in the occipital area, and negatively correlated with auditory stability measures in the temporal and parietal areas. No correlation of age was found with the bimodal stability measures. Large subject differences were found for EP analog waveform amplitude and temporal stability. The EPs were highly stable within subjects from session to session, whether they were recorded hours or months apart. Differences in patterns of waveform stability existed for site and modality conditions across individuals. The degree of intra-subject waveform stability may be considered a personnel assessment measure and has been shown to be related to on-job performance. We will discuss this in greater detail later. Greatest stability was found for the bimodal presentation (r = 0.70-.90), less for the visual records (r = 0.60), and least for the auditory records (r = 0.50). For visual stimuli, mean correlations were 0.70-0.80 in the occipital area, decreasing to about 0.40 in the frontal area. Auditory reliabilities were highest in the frontal/temporal area (0.60), while those for bimodal stimuli were greatest in the parietal/occipital area (0.70-0.90).

Sensory interaction and integration of the visual and auditory modalities appear essential for adequate performance of complex tasks such as reading (Lewis & Froning, 1981; Shipley, 1980). Bimodal records often produce greater amplitude and shorter latency of EP components than visual or auditory records alone, suggesting sensory integration. Integration of the two sensory systems is probably the main contributor to the greater stability of bimodal records compared to that of visual or auditory records taken separately. Data presented in the Lewis (1984) paper suggested that bimodal presentation may activate greater populations of brain fibers, a quantitative factor contributing to waveform stability.

Brain Activity and Ability

The first reporting of human brain activity was by Berger in 1929. Relationships between EEG records and test intelligence date back more than 50 years (Berger, 1933, (cited in Vogel & Broverman, 1964); Kreezer, 1937, 1938, 1939; Kreezer & Smith, 1936, 1937) and dealt with psychopathic personalities and those with lower mental ability. Vogel and Broverman (1964) have reviewed the literature and assessed the positive and negative research results. Their references included 68 citations, most of which were EEG/IQ studies. They suggested that the most consistent EEG/IQ relationships were found for children, for individuals with brain injuries, and for patients with very low mental ability or who have been institutionalized for other reasons. Little relationship was found for normal adult subjects. Vogel and Broverman also pointed out that those researchers who showed negative results often limited their recording sites to the occipital region to obtain occipital alpha (8-13 Hz). Those studies that found EEG/IQ relationships generally used other recording areas (i.e., frontal and parietal). They also suggested that the EEG measures in children were probably related more to absolute mental ability than to IQ. Large differences between subjects in the EEG and EP may be due to differences in age, with very young and old subjects showing longer latencies and larger amplitudes than young adults (Callaway, 1975). They commented on several methodological problems that may have weighed against finding more solid EEG/IQ relationships. These included (1) the measurement of intelligence, which was often confounded with age; (2) EEG recording sites (in areas other than the occipital region); (3) conditions during recording, including the fact that nearly all studies recorded the EEG while subjects were idle and not performing mental tasks; (4) use of subjects of both sexes in the samples, even though large sex differences are reflected in EEG measures; and (5) restricting the EEG measures to the traditional frequency bands (i.e., delta, theta, alpha, beta). Nevertheless, higher frequencies in varying brain regions and the absence of slower delta and theta rhythms were found to be associated with higher levels of intelligence.

One of the earliest EP studies dealing with intelligence was published more than 20 years ago (Chalk & Ertl, 1965), followed by several other papers (Ertl, 1968, 1969, 1971, 1973; Ertl & Schafer, 1969). Ertl proposed the idea that "neural efficiency" is related to

IQ, that is, speed of information processing is related to IQ. Smart subjects would have shorter visual EP latency components than less smart subjects. Ertl later developed and sold the neural efficiency analyzer, which caused much interest and controversy and stimulated a popularization of the approach (Helvey, 1975). Besides the fact that he used unconventional recording locations, Ertl did not use a conventional latency measure. Callaway (1975) covers the relationships between EP latency and intelligence in considerable detail, including the impact that Ertl had in this area of research.

There have been several replications of the Ertl work, including that by Shucard and Horn (1972), Galbraith, Gliddon, and Busk (1970), and Callaway (1975), the latter using Navy recruits. Callaway's own work was reported at length in his book.

Frequency and latency are inversely related, shorter latency being associated with higher frequency. If shorter latency is related to high IQ, then higher frequencies are also related to high IQ. Bennett (1968) studied the relationships between the dominant frequency in the visual EPs of 36 subjects and their IQ scores, as measured by the Wechsler Adult Intelligence Scale. He found a statistically significant correlation of 0.59. Even though he did not report the probability level, using 35 df, the $r = 0.59$ value does exceed the $\alpha = .01$ significance level. Weinberg (1969) studied 42 subjects who had IQ scores ranging from 77 to 146, measured by the verbal portion of the Wechsler Adult Intelligence Scale. EP data were obtained by having the subjects passively observe a visual stimulus. He found that the 12 and 14 Hz frequency components showed statistically significant correlations with IQ test scores.

Ertl (1971) attempted to replicate both the Bennett and Weinberg studies, but was unable to do so. He did suggest that higher IQ subjects tended to show higher frequency components during the first 200 ms of the EP than did the lower IQ subjects. From 200-500 ms, both IQ groups showed about the same frequency component amplitudes. Ertl (1973) found EP/IQ relationships by examining 80-ms windows within the 0-240-ms portion of the EP waveform. Shucard and Callaway (1973) were not able to find statistically significant relationships between EP frequency components and IQ.

Everhart, China, and Auger (1974) tested Ertl's neural efficiency analyzer (NEA) to see if it actually measured visual EPs or not. They found no difference between experimental conditions for the visual stimulus, regardless of whether the stimulus was "on" or "off" or whether the presentation of an auditory stimulus was "on" or "off." They concluded that the NEA was measuring relationships between ongoing EEGs, not EPs, and verbal intelligence. In addition, they suggested that the NEA not be used to assess or predict verbal intelligence because the correlations were too small to be of value.

Major negative findings concerning the NEA were reported by Davis (1971). Virtually no relationships were found ($r = 0.0 \pm .15$). The Davis study, according to Callaway (1975), provided little resolve of the issue due to claims of very noisy data and lack of oversight. Lykken (1973) severely criticized this study and stated that "this 'replication' was a debacle, an enormously expensive, total failure" (p. 463). Rhodes, Dustman, and Beck (1969) and Dustman and Beck (1972) were also unable to replicate EP latency/IQ relationships.

Other aspects of the EP/IQ relationship that have been investigated include recovery functions, which were generally slower for slow learners than for college students (Wasman & Gluck, 1975), and number and amplitude of potentials during conditioning in children, which were found to be weaker for lower IQ subjects (Lelord, Laffont, & Jusseaume, 1976).

In addition to the speed-of-processing theory of intelligence, Hendrickson and Hendrickson (1980) suggested that intelligence is related to error rates in the brain. They proposed that the way information is coded and transmitted within the brain determines the error rates during cognitive processing. HIGH intelligence results from low error rates within the brain. With increased error rate, there is lower EP amplitude and less complexity in the EP waveform components. The "string measure" was used to measure complexity and amplitude by literally laying a string on the waveform and measuring the length. The greater the amplitude and complexity, the longer the string length. Eysenck and Barrett (1985) reviewed at considerable length this error rate theory, as well as other proposed interactions of psychophysiology and intelligence. Blinkhorn and Hendrickson (1982) showed very strong relationships between the string measure and intelligence, as measured by the Raven's Advanced Progressive Matrices (APM). They presented auditory tones to 33 university students and found a correlation of 0.54 between the auditory EP string measure and APM score ($p < .001$).

Vetterli and Furedy (1985) took issue with the string measure used by the Hendricksons based on empirical tests of error theory and speed theory hypotheses.[1] Vetterli and Furedy state that the Hendrickson string measure was not only arbitrary, but the correlations that were found depended on the way in which the EP amplitude and time axes were plotted. They suggested that the greater the ratio of the amplitude to time, the higher the correlation between EP and IQ. This string measure had been revised by the Hendricksons in an attempt to eliminate the arbitrary nature of their measure. Vetterli and Furedy compared this revised string measure with a latency measure and an average voltage measure to assess EP complexity. They used two data sets, one from select subjects used by Ertl and Schafer (1969), and a second smaller data set from Weinberg (1969). Their results tended to support the speed theory rather than the error theory with regard to EP/IQ relationships.

In our early work (Lewis, Rimland, & Callaway, 1977), we used procedures similar to those of Ertl and Schafer (1969) in order to examine the relationship of the neural efficiency measures to aptitude. In our work, the visual stimulus was triggered by the subject's own background EEG activity. The reliability of the EP latency measures was increased by taking into account each subject's background EEG activity. EPs typically crossed the baseline several times within 500-600 msec. We obtained latency measures to the first, second, and third positive-going crossings (i.e., positive-slope zero-cross). Our subjects were 206 Navy recruits who scored high (n = 103) and low (n = 103) on the Armed Forces Qualifications Test (AFQT). The HIGH group scored between the 80-99th centiles on the AFQT, which corresponded to an IQ range of 113-133. The LOW group ranged between the 20-40 centiles on the AFQT, which corresponded to an IQ range of about 87-96. Even though we did not find statistically significant differences between our two groups, the latency values tended to generally follow the expected directions (i.e., HIGH

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[1]It should be pointed out that Vetterli and Furedy incorrectly referenced the Blinkhorn and Hendrickson study as showing EP/IQ correlations between 0.7 and 0.8. Correct correlation (0.54) is cited above. It was the Hendrickson and Hendrickson (1980) study that provided the correlations ranging between 0.7 and 0.8.

group had shorter latencies than did the LOW group--HIGHs = 89, 185, 283 ms; LOWs = 92,189, 290 ms). Also, we did not find statistically significant differences (biserial correlation) between latency measures and criterion grouping of remedial readers (i.e., PASS versus FAIL) (Lewis et al., 1977).

MODELS OF BRAIN PROCESSING

Most of our research has emphasized EP amplitude measures, as they appear to be the most appropriate measures for assessing the models of brain processing that we have been following in the literature. These models include lateral asymmetry, variability (temporal and spatial), and resource allocation. Our work will be discussed within the context of one or more of these theories.

Amplitude

The amplitude measure of early choice was the microvolt root mean square (uVrms). There are several advantages to using the rms measure: It is easily computed, is objective and not dependent on visual inspection and identification of EP components, and has a high correlation with low frequency components, of which the averaged waveforms are primarily composed. Two disadvantages are associated with the use of the rms measure:It does not assess latency, nor does it retain the polarity information of the signal. The rms is computed over a time interval. As such, latency can be fairly well-estimated by narrowing the time interval or window. We have found the uVrms to be effective in assessing individual differences from a large and varied group of subjects, because not all subjects show well-defined EP components (Lewis & Froning, 1981).

In one of our early reports, we examined the relationships between amplitude measures and reading ability (Lewis, Rimland, & Callaway, 1976). The subjects (n = 73) included those from a high-risk group with a greater than average probability of early discharge from the Navy. All subjects were male recruits, with an average age of 19 years, who had been admitted into the Navy despite a rather poor level of reading ability. They scored between the 20th and 40th centiles on the AFQT. In addition, these recruits scored between 3.0 and 5.5 grade levels on the Gates-MacGinitie Reading Test, meaning that they could not read as well as the average 11- or 12-year-old. Some of the recruits (n = 32) improved their reading ability sufficiently to continue on active duty (ACT group), while 41 failed remedial reading training and were discharged from the Navy (DIS group) . The AFQT scores for the groups were 35.7 +/- 7.8 centiles for the ACT group and 33.7 +/-10.0 centiles for the DIS group. Entering reading grade levels were 4.4 +/- 0.7 (ACT) and 3.9 +/- 0.7 (DIS).

A statistically significant biserial correlation (r = 0.32, p < .05) was found between EP amplitude (rms) at the F4 site (Jasper, 1958) and the group criterion (ACT/DIS). A discriminant analysis was performed for the two groups that found statistical differences between them (F = 5.59, p < .025). Cross-validation was obtained using the Training-Test Set procedure (X^2 = 5.56, p < .025). No group differences were found using the trial-to-trial variability or latency measures. Amplitude measures were greater for the ACT group than for the DIS group, which may reflect greater temporal variability for the DIS than for the ACT group. Greater variability, or "jitter," in the single epochs is generally reflected as lower waveform amplitudes in the EP average.

Follow-up performance records were obtained for enlisted recruits 3 years after recording the initial EP data. The primary objective of recording the original EP data was to compare the EP amplitude and asymmetry predictors with the traditional paper-and-pencil aptitude and academic predictors used by the Navy. The subjects were the same used in earlier projects (Lewis et al., 1976, 1977). Not all subjects' records were available for the follow-up research. The sample (N = 173) was divided into two groups based on the number of promotions each enlistee achieved during the preceding 3 years. The HIGH group (n = 102) had two or more promotions, while the LOW group (n = 71) had fewer than two promotions.

Table 1 shows both groups to be fairly similar with respect to GCT scores and highest level of education (HIED) reached. Both groups averaged a 12th grade (high school) level of education. The HIGH group averaged higher in reading grade level RGL (9.5) than did the LOW group (8.9). However, the LOW group scored higher on the AFQT (61 centiles) than did the HIGH group (58 centiles). The mean standardized score for the AFQT is 50 +/- 10 centiles, which suggests that the LOW group averaged one (1) standard deviation above the mean on the AFQT. However, this observation must be considered in light of the fact that both group standard deviations were large (and similar).

Table 1

Reading Grade Level, Aptitude Test Scores, and Highest Education Level Achieved for the HIGH and LOW Promotion Groups

	HIGH		LOW	
	MN	SD	MN	SD
RGL	9.48	2.58	8.93	3.27
GCT	52.53	13.28	52.82	13.88
AFQT	57.75	30.65	61.07	29.01
HIED	12.01	.76	12.06	1.19

Sixteen EP amplitude variables (two series of 50 flashes each for the 8 sites) and four aptitude-academic (traditional paper-and-pencil) variables served as input to a discriminant analysis (DA). The four paper-and-pencil test variables included scores from an aptitude test (AFQT), a classification test (GCT), reading grade level on the Gates-MacGinitie Reading Test (RGL), and the highest grade of education completed (HIED). Five EP amplitude measures (F4, C3, 01, O2, P4) differentiated the two groups ($F = 4.15$, $p < 0.01$) into either the HIGH or LOW promotion group more effectively than did the traditional paper-and-pencil predictors. The hold-out sample procedure (training set, test set) was used for cross-validation and was statistically significant ($X^2 = 9.78$, $p < .005$) with 62 percent of the test set being correctly classified. RGL and AFQT entered the DA at steps 6 and 7 but did not enhance the cross-validation result ($X^2 = 5.03$, $p < .025$). Correctly classified cross-validation cases dropped to 58 percent.

Lateral Asymmetry

The lateral asymmetry model has received much professional and popular press attention (Buchsbaum, & Fedio, 1969; Dimond & Beaumont, 1974; Galin & Ellis, 1975; Kinsbourne, 1972, 1978; Knights & Bakker, 1976; Mintzberg, 1976; Ornstein, 1977, 1978), and critical review (Beaumont, Young, & McManus, 1984). This model suggests that logical, sequential, and analytic processes are performed in the left hemisphere, while spatial, simultaneous, and integrative processes are performed in the right hemisphere.

Asymmetry may be measured as the EP amplitude difference between the left (LH) and right (RH) hemisphere (RH minus LH) for homologous sites. We felt that most paper-and-pencil tests and classroom instruction would primarily assess functions attributed to LH, and that such functions might be assessed through the lateral asymmetry model (Lewis & Rimland, 1979). Many, if not most, Navy on-job and other real-world performance would depend also on the functions usually attributed to RH, for example, requiring integrative, spatial, and judgmental skills. We found few, if any, relationships between lateral asymmetry measures and academic criteria (e.g., remedial reader test scores (Lewis et al., 1976)) or aptitude (AFQT) (Lewis et al., 1977).

In order to assess this model, we used groups of highly skilled personnel. EP data were recorded from 26 sonar operator trainees (Lewis & Rimland, 1980) and 58 aviators (28 pilots, 30 radar intercept officers (RIOs)) in an operational environment (Lewis & Rimland, 1979). The operator of today's sophisticated sonar equipment must perform difficult and demanding mental operations requiring quick processing of visual and auditory information and the visualization of moving objects in three-dimensional space. Although conventional paper-and-pencil aptitude tests are reasonably effective in predicting academic performance in sonar school, they are not effective in identifying, from a pool of applicants, those who are most likely to perform successfully as sonar operators.

Performance measures were obtained from the 26 trainees, which included instructor and peer ratings, aptitude test scores, classroom grades, and laboratory test scores. The laboratory performance scores were based on electronic test equipment operation, aural identification of sonar contacts, visual identification of sonar contacts, and sonar simulator performance. Two groups were formed based on the sonar simulator performance score. Scores on the aptitude tests and laboratory tests were very similar for the two groups (Table 2). The fourth lab test (Sonar Simulator Performance) was used as the criterion. Correlation of the performance score with instructor ratings was significant ($r = -.74$, $p < .01$), as was the correlation with peer ratings ($r = -.60$, $p < .01$). Negative correlations were due to the scoring of rating questions. Instructor and peer ratings agreed well ($r = .66$, $p < .01$). The magnitude of these correlations ($r = .60$-$.74$) attests to the reliability of the measures. Performance score also agreed with overall classroom grade ($r = .35$, $p < .01$). The AFQT score predicted the classroom grade ($r = .47$, $p < .01$), but not the simulator performance score ($r = .06$, NS).

If good simulator performance depended on RH functioning, the high performers should show larger RH amplitude and, therefore, positive asymmetry (i.e., RH > LH). Group differences were found primarily in the occipital region ($F = 5.87$, $p < .025$). The data showed that the high performers had positive asymmetry (0.18 uVrms) in this region, while the low performers had large negative asymmetry (-0.52 uVrms). These asymmetry values showed a difference that was statistically significant ($t = 2.70$, $df = 18$, $p < .02$). The standard deviations for these asymmetry measures were much larger for the low performers (0.75 uVrms) than for the high performers (0.35 uVrms). These findings are also consistent with other research showing the right hemisphere to be heavily involved in tasks relating to the individual's orientation in three-dimensional space. The finding of large differences between the high and low groups in recordings taken from the occipital area is of special interest because of the occipital area's strong role in visual perception. The operational tests used in sonar student selection did not distinguish between the high and low groups (Lewis & Rimland, 1980).

Table 2

Descriptive Statistics for HIGH and LOW Sonar Trainee Performance Groups

Item	HIGH (n=14) MN	HIGH (n=14) SD	LOW (n=12) MN	LOW (n=12) SD
Aptitude Test Scores				
GCT	60.46	6.91	60.33	5.60
ARI	57.23	6.47	57.92	6.37
MECH	54.54	6.98	52.00	6.62
ETST	64.91	4.28	63.25	2.73
AFQT	73.71	13.05	72.33	12.07
Test Scores on Sonar Laboratory Practicals:				
Elect. Test Equip. Oper.	89.25	8.51	86.08	9.39
Aural Ident. of Sonar Contacts	89.36	9.25	88.92	11.07
Visual Ident. of Sonar Contacts	77.17	17.84	73.42	17.45
Sonar Simulator Performance	87.57	4.31	74.92	7.79
Sonar Classroom Grade	75.43	4.88	72.75	5.71
Age	20.54	2.25	19.22	.82

Pilots and RIOs might be considered to represent prototypes of the two different kinds of information processing served by the right and left hemispheres, respectively. Pilots must be able to cope quickly with problems in three-dimensional space and to make correct split-second judgments based on incomplete information (presumably nondominant RH functions). While RIOs must perform many pilot-like tasks, many of their duties require them to deal with explicit information in a sequential, logical, and systematic way (alleged dominant LH functions). Obviously, pilots must also have LH abilities, and RIOs cannot succeed without RH spatial and judgmental abilities. Careful screening of aviation candidates ensures that both pilots and RIOs have above-average intellectual abilities, particularly the more readily measurable LH skills. Nevertheless, the key elements of pilot and RIO performance might be reasonably categorized as primarily right- and left-hemispheric in nature, respectively. This reasoning leads to the hypothesis that the pilot group may be discriminated from the RIO group based on visual EP amplitude measures from the left hemisphere and right hemisphere. This assumes that classification of aviation officers into the pilot and RIO groups, and/or subsequent on-job experience in these respective groups, may lead to a differentiation of the two groups in terms of brain functioning.

A second hypothesis consistent with this reasoning is that the quality of pilot and RIO performance may be a function of the degree to which the pilots possess relatively superior RH abilities and RIOs possess relatively superior LH abilities.

Pilots and RIOs may, in fact, represent prototype groups for hemisphere asymmetry research. Doktor and Bloom (1977) used electrophysiological methods in a similar way in their study of operations researchers (LH) and holistically-oriented company executives (RH). They reported a change from right to left hemisphere of EEG alpha activity (in the temporal area) for the operations researchers when they performed spatial as opposed to verbal tasks. No differences were found for the executive group. Lawyers (primarily verbal, LH) and ceramists (primarily spatial, RH) were used in the Galin and Ornstein (1974) study of hemispheric functioning in contrasting occupational groups. Galin and Ornstein used Kinsbourne's (1972) technique of measuring gaze shift of eyes during thought and in response to questions as indicators of hemispheric activation. Although they found gaze shift differences between lawyers and ceramists, no EEG differences were found between these two groups.

Since the pilots and RIOs performed somewhat different functions, we wished to find if they differed, as groups, in their visual EPs. Any difference found might be due to either selection factors or experience. Initial self-selection to be a pilot or an RIO or explicit selection, as well as self- or operational selection during or after training, could result in groups of pilots or RIOs that were quite dissimilar. It might also be argued that different experiences during or after training cou'd cause EP differences.

Both uVrms mean and standard deviation values of the pilots exceeded those of the RIOs. Discriminant analysis was used to estimate the extent to which the visual EP amplitude measures might differentiate the pilots from the RIOs. EP amplitude measures at the C3 and F3 sites discriminated ($\underline{F} = 6.53$, $\underline{df} = 1, 56$, $p < .025$) and correctly classified 71 percent of the aviators.

In addition to our interest in possible group differences between pilots and RIOs, we wished to determine if individual differences in performance within the pilot and RIO groups might be reflected in EP measures.

It had been hypothesized that high-rated pilots would show greater RH activity than low-rated pilots, and that high-rated RIOs would exhibit greater LH activity. Each of the 28 pilots and 30 RIOs was compared to the other pilots and RIOs, respectively, on a scale of 1 to 10. Ratings were obtained from their operations officer, a former Navy Blue Angel aviator qualified to assess flying proficiency as well as ground school performance. To test these hypotheses, asymmetry values were computed from homologous sites in the frontal, central, parietal, and occipital regions (i.e., RH minus LH in each of the four regions) and plotted against the performance ratings for the pilot and RIO groups. The percentage of aviators rated 8, 9, and 10 whose RH amplitude was greater than their LH amplitude was then determined. The clearest asymmetry relationship was seen in recordings from the parietal region (Figure 1).

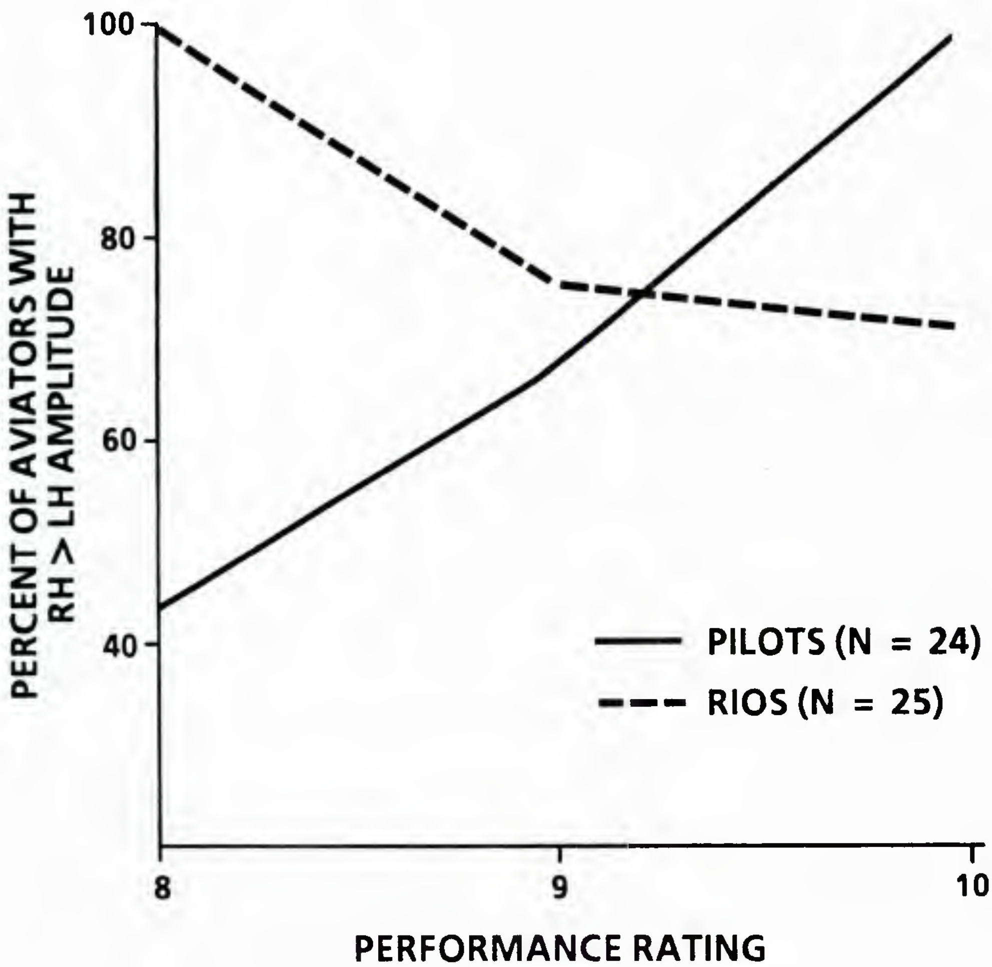

Figure 1. Percent of right-handed aviators with parietal RH amplitude greater than LH who were rated 8, 9, or 10 on a scale of 1 to 10 by their operations officer.

Several limitations of this study should be noted. First, the samples were composed of experienced aviators; thus, the results were confounded by restriction of range and the effects of experience. Second, the number of subjects tested was too small to permit cross-validation of findings. Third, pilot and RIO performances were rated by only one person and were of limited range and reliability. Ideally, objective performance and/or simulator-derived proficiency measures should be used. Finally, the stimulus used to evoke the brain potentials consisted of a simple flashing light. No dynamic task was performed.

Despite the limitations of this study, several promising findings were observed. These included EP differences between pilots and RIOs that provided preliminary confirmation of the hypothesized differences between right hemisphere and left hemisphere functioning in pilots and RIOs.

In discussing the EP differences between pilots and RIOs, we noted the possibility that the EP findings could be the result of endogenous and/or experiential factors. Subsequent analyses relating flight experience to the EP measures showed markedly greater EP asymmetry dispersion among aviators (pilots and RIOs) with a moderate amount of flight experience (900-1500 hours) than among those with a larger amount of experience (1600-2400 hours) (Lewis & Rimland, 1979).

We have found the asymmetry model to have limited usefulness for personnel assessment. We have found asymmetry in active duty, average ability personnel, but not discharged enlistees, remedial readers, and lower aptitude subjects (Lewis, 1983b). There may be specialization of some hemispheric function, but it has been difficult to show consistent relationships to on-job performance in other areas of our research.

Variability

Perhaps a more appropriate model for our research involves brain variability and its converse, brain stability. Differences in performance are related to the degree to which brain recordings vary. Research in the areas of functional psychiatric disorders (i.e., schizophrenia) and effects due to age has made substantial contributions to the development of this model (Callaway, 1975; Callaway & Halliday, 1973; Callaway et al., 1970; Shagass, 1972). We have found that "normal" populations also show variability in brain recording. Consistently, we have seen through much of our research that high temporal and spatial variability in the brain is often associated with low performers. High performers generally show less variability and more intra- and inter-subject brain stability than do low performers.

Intra-subject Variability

Intra-subject variability may be assessed by using the trial-to-trial EP variability measure. In a study reported earlier (Lewis et al., 1977), we examined a group of recruits ($N = 206$). Half of the recruits were classified as having low aptitude (20-40th centiles on the AFQT), while the other half were classified as having high aptitude (80-99th centiles). Large group differences were found ($t = 2.97$, $df = 204$, $p < .01$) when the trial-to-trial variability measure was used to differentiate between the high and low aptitude groups. The HIGH group showed less variability ($MN = 7.56 +/- 1.38$ uVrms) than did the LOW group ($MN = 8.29 +/- 2.03$ uVrms).

Inter-subject Variability

Whereas the trial-to-trial variability is used for intra-individual variability measurement, the standard deviation of the sample or group is used to measure the dispersion or inter-subject variability. In the aviator study, recordings were made from four paired sites: frontal, central, parietal, and occipital. In order to provide general front-to-back comparisons, frontal and central asymmetry values were combined (front), as were parietal and occipital (back). Data were analyzed for the front and back combined sites. In addition we were interested in the dispersion of these measures as they relate to performance rating. The standard deviation statistic, which measures dispersion of a sample, may also provide information about individual and group differences. Such dispersion was assessed in our aviator (Lewis & Rimland, 1979) and sonar operator (Lewis & Rimland, 1980) research. One finding, has been consistent over several projects, is illustrated in Figure 2. This figure shows the standard deviations (SDs) plotted for the pilots and RIOs, their performance ratings (high and low), and electrode sites (front and back). Left-handed and ambidextrous subjects were removed from the sample because it was thought that hemisphericity might be mixed in these subjects. The SDs for both the high-rated pilots and high-rated RIOs were about equal at the front and back sites, with the SDs slightly larger for the back than for the front sites. The SDs obtained for the low-rated groups at the front and back sites were greater than those for the corresponding high-rated groups. Further, the SDs obtained for low-rated pilots at the front and back sites were greater than those obtained for low-rated RIOs at these sites. As with the high-rated pilot and RIO groups, the SDs for the low-rated pilot and RIO groups were greater for the back than for the front sites. The front-to-back differences were considerably greater for the low groups.

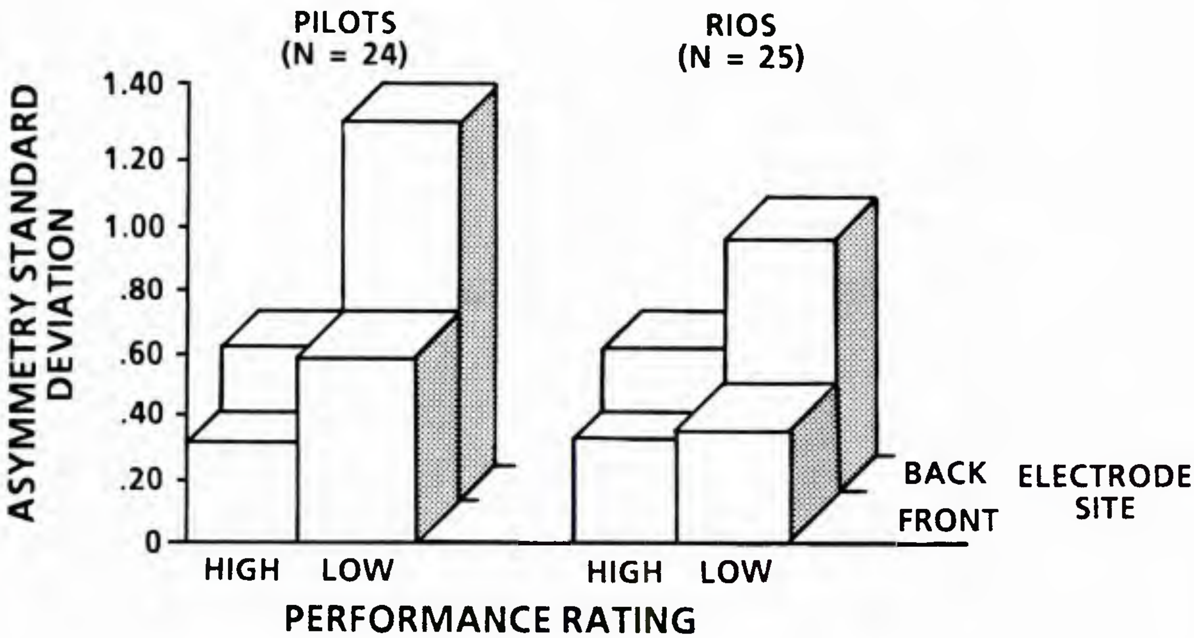

Figure 2. Asymmetry standard deviations for the HIGH- and LOW-rated pilots and RIOs.

The back electrode sites included an association area (parietal) and the primary visual reception area (occipital). The front site included both an association area (frontal) and a sensory-motor area (central). The experimental task was passive, requiring only that the subjects observe a blinking light.

An observation in this project dealt with EP habituation--another source of variability (Lewis, 1979). Visual EP habituation was assessed by comparing the EP records from the first 50 flashes with the second 50 flashes. The instructor pilots showed visual EP habituation ($F = 5.98$, $df = 1, 27$, $p < 0.02$), while the student pilots did not. This suggested that perhaps the instructors may have adapted more quickly to the experimental conditions and were less aroused than the students.

Relationships between asymmetry dispersion and performance for the sonar operator trainees were similar to those for the aviators (Figure 3). Again, only right-handed subjects (HIGH, n = 10, LOW, n = 10) were included. The SDs, or asymmetry dispersion measures, were similar from the front and back electrode sites for the HIGH group. Greater front-to-back differences were found for the LOW group than for the HIGH group. Finally, there was less dispersion in both front and back regions for the HIGHs compared with the LOWs.

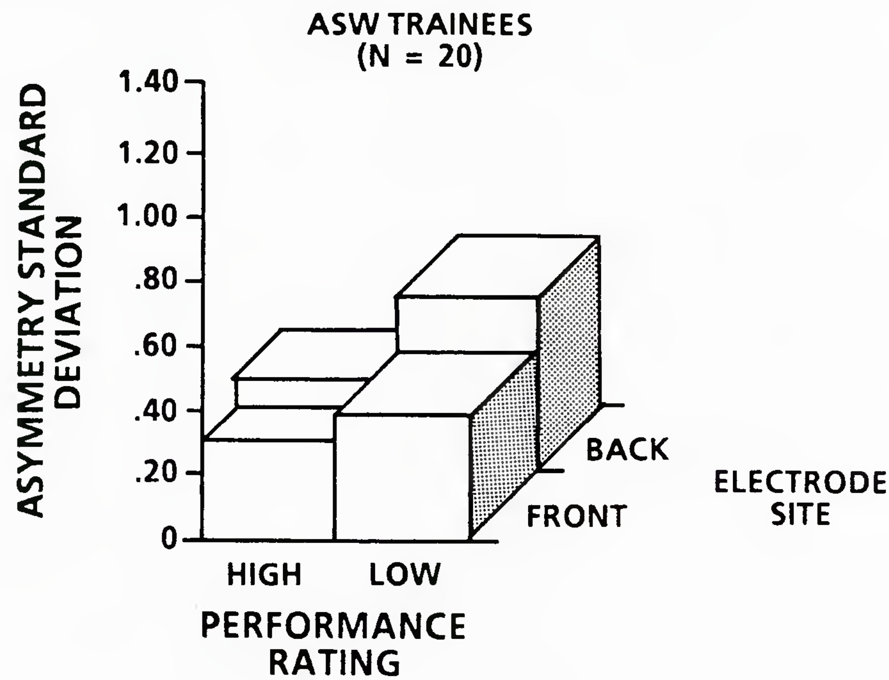

Figure 3. Asymmetry standard deviations for HIGH- and LOW-rated sonar operator trainees.

Resource Allocation

The third model, resource allocation (Broadbent, 1958; Coles & Gratton, 1985; Isreal, Chesney, Wickens & Donchin, 1980; Wickens, 1980), is also being followed in our research on decision making under varying workload conditions (Trejo, 1986). Each individual has finite resources to devote to a particular activity. The proportion of resources which may be dedicated to an activity or problem may also be assessed by neuroelectric and neuromagnetic procedures. One of the procedures used in neuroelectric assessment of cognitive function involves presenting to the subject an irrelevant probe stimulus, such as a flash of light or clicks to the ears. While performing a task or simulated task, an individual is presented stimuli, which he or she is told to disregard. These stimuli are the irrelevant (to the task) probes used to generate the EP. The probes are most often visual or auditory stimuli. The model suggests that as mental resources are used in performing the task, fewer resources are available for processing the probe stimulus. Consequently probe-generated EP component amplitude would be expected to decrease and component latency increase as a result of increased resource demands from the primary task. Papanicolaou and Johnstone (1984) have reviewed the use of the irrelevant probe technique and allocation of resources model in cognitive processing.

In a recent report, Trejo (1986) discussed the assumptions, hypotheses, and experimental designs in using neuroelectric, and possibly neuromagnetic, signals as predictors or correlates of decision making by combat system operators. Such decision making would occur under varying workload conditions. He discussed the application and relevance of signal detection theory (Green & Swets, 1966) to the behavorial aspects of the decision-making task. The influence of perceptual sensitivity on signal detection was discussed as was the response bias of individuals performing decision-making tasks. Decision making implies an outcome of the process. Individuals generally assign an expected value or utility to decision alternatives. Trejo discussed the implications of the subjective expected utility theory (Whalen, 1984; Wright, 1984) for the decision-making tasks. An individual's assessment of decision outcome probability may be influenced by personality-like factors, such as risk-aversion or risk-taking strategies. Trejo states that most decision makers are risk-aversive, which obviously influences the strategy in reaching a decision.

Trejo, Lewis, and Blankenship (1987a) reported on irrelevant probe EP data acquired during the performance of the Air Defense Radar Simulation Task (AIRDEF); (Kelly, Greitzer, & Hershman, 1981; Trejo, 1986). The subject views two concentric circles on a graphics monitor. The outer circle represents the range of a simulated ship-board radar system. Range of the ship's weapon is represented by the inner circle. The subjects are to imagine that they are onboard the ship, represented by a cross at the center of the two concentric circles. Incoming hostile missiles appear at any point on the outer circle (radar range) and proceed toward the center (subject's own ship) at one of three speeds (fast, medium, slow). The subjects are required to make a decision as to when to fire anti-missile weapons. Obviously, subjects must fire their weapons earlier for a fast incoming missile than for a slow missile. The objectives are to (1) not take "hits" on one's own ship, (2) "kill" all of the incoming missiles at a maximum range, and (3) not fire more than one weapon on the same incoming missile track number. Workload is varied by presenting 18 targets during one condition and 36 during another.

A baseline condition, where no targets were presented, was used to represent resources undiminished by task performance. During the task, the subject observed, but was told to ignore, dim flashes on the graphics monitor. These flashes were presented aperiodically and provided the visual stimulus to generate the EP epochs for averaging. Forty-five male subjects performed the AIRDEF task. Eight channels of EP data were obtained from the frontal, temporal, parietal and occipital regions of each subject.

As stated earlier, the resource allocation model predicts that as resources are allocated and used to perform a task, fewer resources are available to "process" the irrelevant probe stimulus. One expects, then, that EP amplitudes would decrease from baseline to active-workload conditions. Trejo et al. (1987a) used two EP measures to assess the effects of workload on decision making during AIRDEF. The first was a traditional signal-averaged EP ($\underline{n}$ = 6 epochs per average) and resulting root mean square (RMS) amplitude (Callaway, 1975; Lewis & Froning, 1981). The metric for this waveform was designated as RMS-a, expressed in microvolts (uV). The second measure was a signal-to-noise ratio, similar to that used by John et al. (1983). The latter waveform was expressed as a ratio of the arithmetic mean to the unbiased standard deviation of corresponding time points for each of the six epochs. The signal-to-noise measure was used also to minimize large random components that may be artifact. The root mean square was obtained for this waveform and was expressed as RMS-s. The latter units were dimensionless because both mean and standard deviation values contained the same units (uV).

Trejo et al. (1987a) used repeated measures analysis of variance to evaluate the effects of workload (baseline, 18 targets, 36 targets), recording sites, and time windows within each EP. The two workload conditions translated to 4.5 and 9 targets per minute for the 18 and 36 targets, respectively. Recording sites included those from the frontal (F3, F4), temporal (T3, T4), parietal (P3, P4) and occipital (01, 02) regions. Because no hemisphere-related differences were found, the mean of the homologous site RMS values was used. Eight time windows were analyzed within the EP waveforms, each about 50 ms wide, extended from about 50 ms through 450 ms. RMS values were computed for each window.

Results showed that workload did decrease the amplitude (RMS-s) of the EP waveform by about 25 percent when compared with baseline (F = 10.97, df = 2, 58, p < .001), as predicted by the resource allocation model. Main effect for site was also highly statistically significant (F = 22.38, df = 3, 87, p < .001), as was the main effect for time window (F = 10.48, df=7, 203, p < .001). A three-way interaction (workload x site x time window) was significant (F = 2.44, df = 42, 1218, p < .001). This interaction suggested that certain components (time windows) at particular sites were sensitive to workload. Specifically, frontal amplitude decreased by 47 percent in the latency interval 100 - 150 ms (F = 54.75, df = 1, 5664, p < .001), by 38 percent in the 250 - 300 ms interval (F = 20.84, df = 1, 5664, p < .001), and 39 percent between 300 - 350 ms (F = 23.66, df = 1, 5664, p < .001). Amplitudes in the parietal region decreased 41 percent during the 200 - 250 ms interval (F = 48.74, df = 1, 5664, p < .001). Occipital amplitudes decreased 8 percent in the 100 - 150 ms interval (F = 6.58, df = 1, 5664, p < .025), and decreased 29 percent between 200 - 250 ms (F = 24.04, df = 1, 5664, p < .001). Similar effects were noted for the traditional amplitude measure (RMS-a); however, no main effect for workload was found. Frontal amplitudes decreased 40 percent during the 100-150 ms interval (F = 36.54, df = 1, 5664, p < .001), 33 percent between 250-300 ms (F = 17.85, df = 1, 5664, p < .001), and 40 percent during the 300-350 ms interval (F = 30.18, df = 1, 5664, p < .001). Parietal amplitude decreased 46 percent between 200-250 ms (F = 53.83, df = 1, 5664, p < .001); however, amplitude in the occipital region increased 13 percent between 100-150 ms (F = 10.63, df = 1, 5664, p < .001) and decreased 29 percent between 200-250 ms (F = 51.32, df = 1, 5664, p <.001).

Relationships between these data and on-job performance have also been found (Trejo, Lewis, & Blankenship, 1987b). On-job performance data dealt with military and job knowledge and performance, reliability and motivation. Two groups (HIGH and LOW) were formed based on these data. The mean age for the HIGH group (n = 16) was 21 +/- 2 years, while that for the LOW group (n = 10) was 20 +/- 1 years.

EP amplitude measures (RMS-a) showed a relationship between on-job performance and workload effects. The two groups had statistically significant amplitude differences (workload minus baseline) at two windows centered at 175 ms and 325 ms. There was about a 2 uVrms decrease from the workload and baseline condition for the HIGH group and little or no decrease for the LOW group. One interpretation may be that individuals in the HIGH group may be better able to shift resources from the probe to the task engagement than those in the LOW group.

NEW TECHNIQUES FOR MEASURING BRAIN ACTIVITY

For the past several years, NPRDC has been developing neuromagnetic (evoked fields, EF) recording capability to assess brain processing and "index" on-job performance. These recordings have several advantages over traditional neuroelectric procedures. (1) They represent an absolute measure, compared with the EEG/EP, which is a relative measure between an active site and a relatively "indifferent" reference electrode. Activity at the reference site often complicates interpretation of the EP data and makes precise location of brain activity difficult. (2) With EF recordings, there is little or no effect on, or "smearing" of, the neuromagnetic field due to skull capacitance or skull-scalp tissue interface. EF activity, therefore, has higher spatial resolution than does EP activity. (3) The EF may also provide information in addition to what may be obtained using the EP. Because of these advantages, we may be able to increase our capability to assess individual differences and, therefore, predict on-job performance (Lewis, 1983a; Lewis & Blackburn, 1984). Improving technology and methodology in order to obtain single epochs (unaveraged records) would provide more accurate assessment of short-term brain processing. Two years ago we reported on EF single epoch recordings as well as test-retest EF reliability, the first such reports to appear in the literature (Lewis, Blackburn, Naitoh, & Metcalfe, 1985). Recent research at the Center has suggested that neuromagnetic recordings may predict on-job performance better than neuroelectric recordings.

EP and EF data were recently obtained in a military operational environment for the first time and EP and EF relationships were found with on-job performance (Lewis et al., 1986). These data were obtained from 26 Marine Corps personnel. On-job performance criteria data were obtained by supervisor ratings and dealt with military and job knowledge and performance, reliability, and motivation. The supervisor rated each subject as "high," "satisfactory," or "low" for each of the above criteria. Two groups (HIGH and LOW) were determined from the ratings. The criterion for assignment to the HIGH group was "high" ratings in all categories. One or more ratings of less than "high" resulted in assignment to the LOW group. The entire sample of subjects should be considered fairly homogeneous because they all were similar in age, had been in the military for 4 years, were all males, and were highly selected for security positions.

Correlation between the HIGH:LOW job performance rating given in 1985 and their rank in 1987 based on Marine Corps records was 0.79 ($p < .0002$). To the extent that as rank indicates on-job performance quality, the HIGH:LOW job rating may be considered a reasonable index of performance. The mean age for the HIGH group ($n = 16$) was 21 +/- 2 years, while that for the LOW group ($n = 10$) was 20 +/- 1 years. Data were also obtained from two standardized tests, the Cognitive Laterality Battery (CLB) (Gordon, 1983) and the Test of Attention and Interpersonal Style (TAIS) (Nideffer, 1977). The CLB is a series of tests that assess cognitive functions such as verbal/sequential and visuospatial processing. It has been used with such diverse occupational groups as combat pilot trainees, bank employees, and computer programmers. The TAIS is a self-report inventory that assesses the respondent's ability to control attention and interpersonal factors. Such factors have been suggested as important in emergency situations, competitive athletics, and business. This test has been used as a personnel selection battery for occupations, including police officers.

Each subject viewed (binocular, central fixation) a black and white checkerboard pattern subtending 5 degrees visual angle (VA) at a luminance of about 34 cd/sqm. Each check subtended 0.4 degrees VA. The stimulus was flashed on for 10 msec. Intertrial interval varied between 500 and 1500 msec. Background luminance was about 3 cd/sqm.

EP data were recorded using a commercially available electrode helmet (Electro-Cap International[2]), amplified (20,000 gain) and bandpassed (0.1-100 Hz; Grass amplifiers, model 12A5). Ten channels of data were obtained; however, data from only two sites (visual reception/occipital area 01, 02) will be discussed here. EF recordings were obtained using a DC SQUID Biomagnetic Detection System (B.T.I., Inc. model 600B, second derivative gradiometer). The single channel EF signal (1000 gain on the SQUID control unit) was bandpassed (0.1-40 Hz Krohn-Hite, mode 3343) and further amplified (50 gain, Grass P511J) prior to digital conversion. Sampling rate for the EP and EF recording was 256 Hz. Post-stimulus record lengths were one-half second. EPs were averaged over 7 epochs, while EFs were averaged over 19 epochs.

All EP and EF data were acquired and stored as single epochs on a field-portable computer system (MASSCOMP, model MCS-5500). The unit of measure for the EPs was the microvolt (uV), while that for the EF was the femtotesla (fT) (10^{-15} Tesla). Sample EP and EF data recorded over the left (01) and right occipital (02) areas appear in Figure 4. More precisely, the EF data were recorded 1 cm lateral to the 01 and 02 EP sites. However, for convenience, the EF site locations will be referred to as 01 and 02. Note the similarity in the EP data recorded over the two separate areas (01 versus 02) and the polarity reversal in the EF data recorded from the same general areas (01 versus 02). For both the EP and EF records, root mean square (rms) amplitudes were obtained from each single epoch and the averaged data.

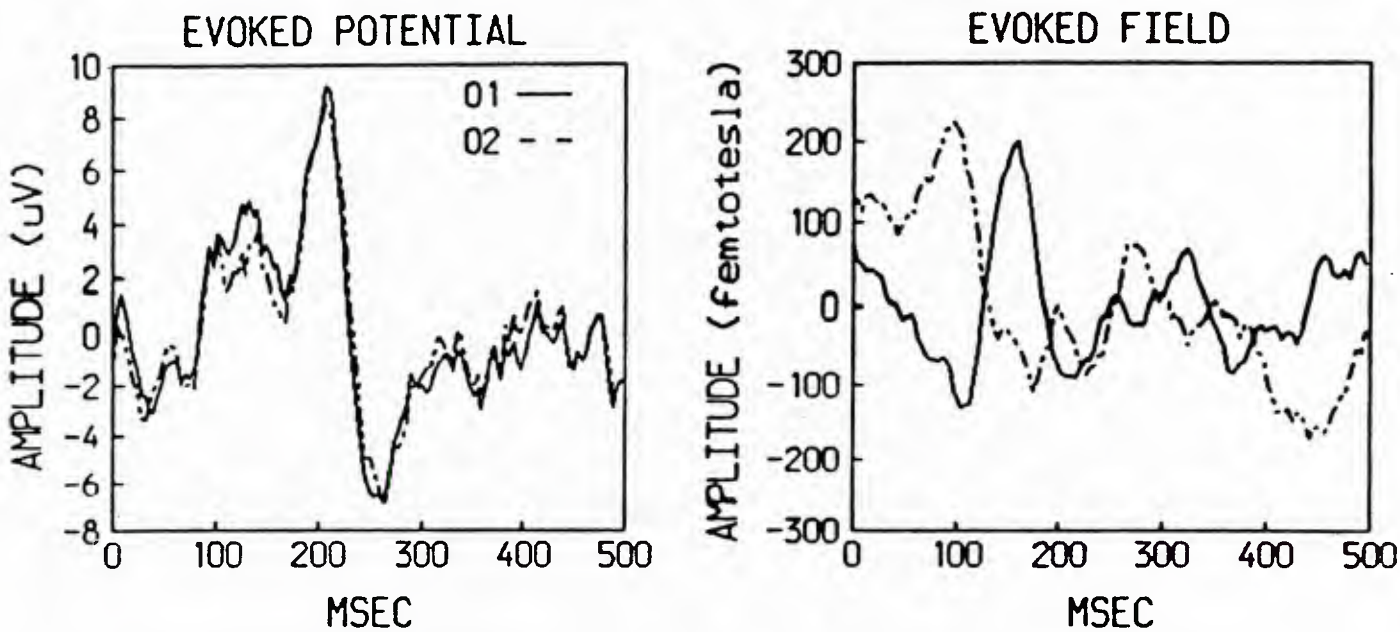

Figure 4. Sample EP and EF data (from Lewis et al., 1986).

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[2]Identification of equipment is for documentation only and does not imply endorsement.

Neither the TAIS nor the CLB scores were able to distinguish the HIGH group from the LOW group (t-test). The CLB did show that both groups of security personnel performed better on tests of visuospatial function than on verbal/sequential tests (nonparametric sign tests, $p < .02$). This finding suggests that the subjects were a homogeneous sample .

Mean, standard deviation, coefficient of variation (CV = SD/MN) and t-test data for EP and EF recordings, sites, and performance groups appear in Table 3. Three LOW group and two HIGH group subjects lacked EP data, reducing the group sizes to $n = 7$ and $n = 14$ for the LOW and HIGH groups, respectively. The LOW group had lower amplitudes than did the HIGH group for EP and EF recordings over both sites (01 and 02). Evoked potential CVs were about the same for both LOW and HIGH groups; however, they were much greater for the LOW than for the HIGH group at both EF recording sites. Group differences were found for the EP data at site 01 ($p < .05$) and for the EF data at site 02 ($p < .003$). Even though the EF SDs were about the same for both groups at site 02, the mean value for the HIGH group was nearly two times that for the LOW group (Table 3, Figure 5). Largest group differences were seen at the EF site 02, which is reflected in the large t-test value and p value in Table 3.

Table 3

Descriptive and Inferential Statistics for Evoked Potentials and Evoked Fields, Sites, and Performance Groups

	Evoked Potentials (μVrms)				Evoked Fields (fTrms)			
	Site 01		Site 02		Site 01		Site 02	
	Low (n=7)	High (n=14)	Low (n=7)	High (n=14)	Low (n=10)	High (n=16)	Low (n=10)	High (n=16)
MN	5.00	6.99	4.83	6.73	217	272	173	331
SD	1.70	2.20	1.71	2.47	145	105	115	119
CV	.34	.31	.35	.37	.67	.39	.66	.36
t	2.08		1.81		1.12		3.33	
df	19		19		24		24	
p	.05		.08		.27		.003	

EP data recorded over the left hemisphere occipital (i.e., vision reception) area were able to statistically differentiate the HIGH from the LOW groups ($t = 2.08$, $df = 19$, $p < .05$). Those EP data recorded over the right hemisphere did not show statistically significant group differences. EF data were able to show performance group differences to a much greater degree than did the EP data ($t = 3.33$, $df = 24$, $p < .003$). EF temporal and spatial variability was found to be greater for the LOW group than for the HIGH group, a finding that supports the results from our earlier EP research. Our data suggest that inter-individual and inter-group differences may be more pronounced with EF recordings than with EP. Improved localization of the EF recording over the EP recording may, in part, account for increased sensitivity to individual and group differences. Both the EF and EP findings showed group differences that were not seen by either the CLB or TAIS tests. Neither the CLB nor the TAIS test scores correlated with job performance.

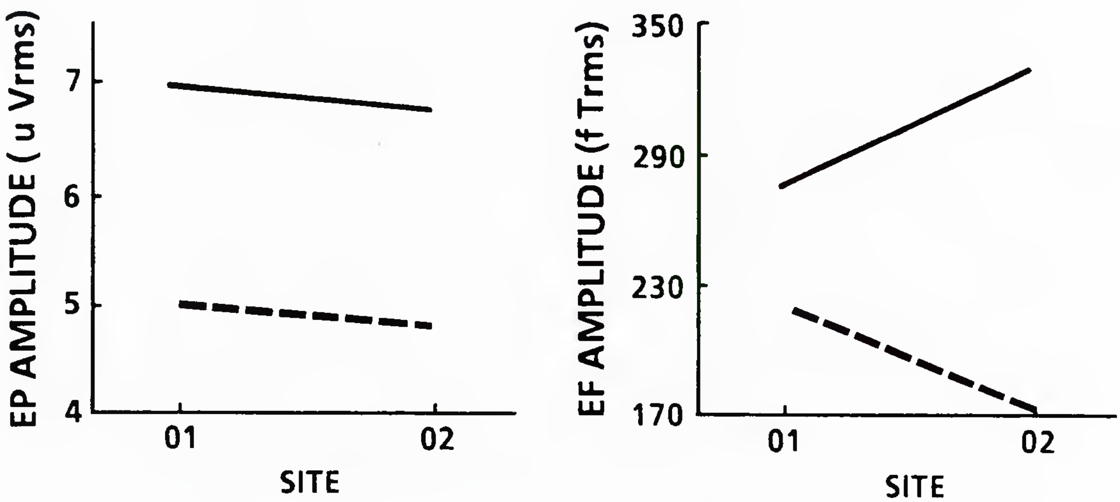

Figure 5. Group mean values for EP and EF data at sites 01 and 02. HIGH group drawn in solid lines, LOW group in dashed lines.

In conclusion, the Navy Personnel Research and Development Center has been exploring the use of neuroscience technologies to improve personnel assessment. Such assessment includes improving the prediction of on-job performance, fitness for duty, selection, and classification. Other research areas include information processing during decision making. Various levels of workload are being used during the performance of realistic simulations to assess decision making. Research is continuing in the area of personnel reliability. Recent operational-recorded EF findings demonstrate that neuromagnetic recordings can be obtained outside of a highly controlled laboratory environment and can be related to on-job performance (Lewis, Trejo, Nunez, Weinberg, & Naitoh, 1987).

REFERENCES

Beaumont, J.G., Young, A.W., & McManus, I.C. (1984). Hemisphericity: A critical review. Cognitive Neuropsychology, 1, 191-212.

Bennett, W.F. (1968). Human perception: A network theory approach. Nature, 220, 1147-1148.

Berger, H. (1933). Uber das Electroenkephalogram des Menschen. Archiv fur Psychiatrie und Nervenkrankheiten, 98, 231-254.

Berkhout, J., & Walter, D.O. (1968). Temporal stability and individual differences in the human EEG: An analysis of variance of spectral values. IEEE Transactions on Bio-Medical Engineering, BME-15, 165-168.

Blinkhorn, S.F., & Hendrickson, D.E. (1982). Averaged evoked responses and psychometric intelligence. Nature, 295, 596-597.

Boring, E.G. (1950). A history of experimental psychology. New York: Appleton-Century-Crofts.

Brazier, M.A.B. (1962). The analysis of brain waves. Scientific American, 206, 142-153.

Broadbent, D. (1958). Perception and communication. Oxford: Pergamon Press.

Buchsbaum, M., & Fedio, P. (1969). Visual information and evoked responses from the left and right hemispheres. Electroencephalography and Clinical Neurophysiology, 26, 266-272.

Buchsbaum, M.S., & Coppola, R. (1977). Signal-to-noise ratio and response variability in affective disorders and schizophrenia. In Begleiter, H. (Ed), Evoked brain potentials and behavior (pp. 447-465). New York: Plenum Press.

Buchsbaum, M.S., Henkin, R.J., & Christiansen, R.L. (1974). Age and sex differences in averaged evoked responses in a normal population, with observations on patients with gonadal dysgenesis. Electroencephalography and Clinical Neurophysiology, 37, 137-144.

Buchsbaum, M., & Pfefferbaum, A. (1971). Individual differences in stimulus intensity response. Psychophysiology, 8, 600-611.

Buss, A.R., & Poley, W. (1976). Individual differences: Traits and factors. New York: Gardner Press.

Callaway, E. (1975). Brain electrical potentials and individual psychological differences. New York: Grune & Stratton.

Callaway, E., & Halliday, R.A. (1973). Evoked potential variability: Effects of age, amplitude and methods of measurement. Electroencephalography and Clinical Neurophysiology, 34, 125-133.

Callaway, E., Jones, R.T., & Donchin, E. (1970). Auditory evoked potential variability in schizophrenia. Electroencephalography and Clinical Neurophysiology, 29, 421-428.

Chalk, F.C.R., & Ertl, J. (1965). Evoked potentials and intelligence. Life Sciences, 4, 1319-1322.

Cohen, R. (1972). The influence of task-irrelevant stimulus-variations on the reliability of auditory evoked responses in schizophrenia. In A. Fessard & G. Lelord (Eds.), Human neurophysiology, psychology, and psychiatry. INSERM Colloquium on "Averaged Evoked Responses and their Conditioning in Normal Subjects and Psychiatric Patients." (Tours, France, 22-23 Sep 1972).

Coles, M.G.H., & Gratton, G. (1985). Psychophysiology and contemporary models of human information processing. In D. Papakostopoulos, S. Butler, & I. Martin (Eds.), Clinical and experimental neuropsychophysiology. London, England: Croom Helm, Ltd.

Dahlstrom, W.G. (1985). The development of psychological testing. In G.A. Kimble & K. Schlesinger (Eds.). Topics in the history of psychology: Vol. 2 (pp. 63-113). Hillsdale, NJ: L. Erlbaum Associates.

Davis, F.B. (1971). The measurement of mental capability through evoked potential recordings. Greenwich, CN: Educational Records Bureau.

Davis, H., & Davis, P.A. (1936). Action potentials of the brain in normal persons and in normal states of cerebral activity. Archives of Neurology and Psychiatry, 36, 1214-1224.

Dillon, R.F. & Wisher, R.A. (1981). The predictive validity of eye movement indices for technical school qualifying test performance. Applied Psychological Measurement, 5 (1), 43-49.

Dimond, S.J., & Beaumont, J.G. (Eds.). (1974). Hemisphere function in the human brain. New York: John Wiley.

Doktor, R., & Bloom, D.M. (1977). Selective lateralization of cognitive style related to occupation as determined by EEG alpha asymmetry. Psychophysiology, 14, 385-387.

Dustman, R.E., & Beck, E.C. (1963). Long-term stability of visually evoked potentials in man. Science, 142, 1480-1481.

Dustman, R.E., & Beck, E.C. (1969). The effects of maturation and aging on the wave form of visually evoked potentials. Electroencephalography and Clinical Neurophysiology, 26, 2-11.

Dustman, R.E., & Beck, E.C. (1972). Relationship of intelligence to visually evoked responses. Electroencephalography and Clinical Neurophysiology, 33, 254.

Ellingson, R.J. (1970). Variability of visual evoked responses in the human newborn. Electroencephalography and Clinical Neurophysiology, 29, 10-19.

Ellingson, R.J., Danahy, T., Nelson, B., & Lathrop, G.H. (1974). Variability of auditory evoked potentials in human newborns. Electroencephalography and Clinical Neurophysiology, 36, 155-162.

Ellingson, R.J., Lathrop, G.H., Danahy, T., & Nelson, B. (1973). Variability of visual evoked potentials in human infants and adults. Electroencephalography and Clinical Neurophysiology, 34, 113-124.

Ertl, J.P. (1968). Evoked potentials, neural efficiency and I.Q. Paper presented at the International Symposium for Biocybernetics, Washington, DC.

Ertl, J.P. (1969). Neural efficiency and human intelligence (Final Report) (Project No. 9-0105). Washington, DC: Department of Health, Education, & Welfare.

Ertl, J.P. (1971). Fourier analysis of evoked potentials and human intelligence. Nature, 230, 525-526.

Ertl, J.P. (1973). I.Q., evoked responses and Fourier analysis. Nature, 241, 209-210.

Ertl, J.P., & Schafer, E. (1969). Brain response correlates of psychometric intelligence. Nature, 223, 421-422.

Everhart, J.D., China, C.L., & Auger, R.A. (1974). Measures of EEG and verbal intelligence: An inverse relationship. Physiological Psychology, 2, 374-378.

Eysenck, H.J., & Barrett, P. (1985). Psychophysiology and the measurement of intelligence. In C.R. Reynolds & V.L. Willson (Eds.), Methodological and statistical advances in the study of individual differences (pp. 1-49). New York: Plenum Press.

Fein, G., Galin, D., Johnstone, J., Yingling, C.D., Marcus, M., & Kiersch, M.E. (1983). EEG power spectra in normal and dyslexic children. I. Reliability during passive conditions. Electroencephalography and Clinical Neurophysiology, 55, 399-405.

Galbraith, G.C., Gliddon, J.B., & Busk, J. (1970). Visual evoked responses in mentally retarded and nonretarded subjects. American Journal of Mental Deficiency, 75, 341-348.

Galin, D., & Ellis, R.R. (1975). Asymmetry in evoked potentials as an index of lateralized cognitive processes: Relation to EEG alpha asymmetry. Neuropsychologia, 13, 45-50.

Galin, D., & Ornstein, R. (1974). Individual differences in cognitive style: I. Reflective eye movements. Neuropsychologia, 12, 367-376.

Ghiselli, E.E. (1966). The validity of occupational aptitude tests. New York: John Wiley.

Ghiselli, E.E. (1973). The validity of aptitude tests in personnel selection. Personnel Psychology, 26, 461-477.

Glaser, E.M., & Ruchkin, D.S. (1976). Principles of neurobiological signal analysis. New York: Academic Press.

Gordon, H.W. (1983). The Cognitive Laterality Battery. Pittsburgh: University of Pittsburgh, Western Psychiatric Institute and Clinic, Media Productions Services.

Green, D.M., & Swets, J.A. (1966). Signal detection theory and psychophysics. New York: John Wiley.

Hadley, J.M. (1940). Some relationships between electrical signs of central and peripheral activity: I. During rest. Journal of Experimental Psychology, 27, 640-656.

Hadley, J.M. (1941). Some relationships between electrical signs of central and peripheral activity: II. During mental work. Journal of Experimental Psychology, 28, 53-62.

Helvey, T.C. (1975). Learning disability measurement with the synchrocephalograph. Journal of Experimental Education, 44, 18-25.

Hendrickson, D.E., & Hendrickson, A.E. (1980). The biological basis of individual differences in intelligence. Personality and Individual Differences, 1, 3-33.

Henry, C.E. (1941a). Electroencephalographic individual differences and their constancy: I. During sleep. Journal of Experimental Psychology, 29, 117-132.

Henry, C.E. (1941b). Electroencephalographic individual differences and their constancy: II. During waking. Journal of Experimental Psychology, 29, 236-247.

Hoagland, H., Cameron, D.E., Rubin, M.A., & Tegelberg, J.J. (1938). Emotion in man as tested by the delta index of the electroencephalogram: II. Simultaneous records from cortex and from a region near the hypothalamus. Journal of General Psychology, 19, 247-261.

Hunt, E., & Pellegrino, J. (1985). Using interactive computing to expand intelligence testing: A critique and prospectus. Intelligence, 9, 207-236.

Hunter, J.E., & Hunter, R.F. (1984). Validity and utility of alternative predictors of job performance. Psychological Bulletin, 96, 72-98.

Isreal, J.B., Chesney, G.L., Wickens, C.D., & Donchin, E. (1980). P300 and tracking difficulty: Evidence for multiple resources in dual-task performance. Psychophysiology, 17, 259-273.

Jasper, H. (1958). The ten-twenty electrode system of the International Federation. Electroencephalography and Clinical Neurophysiology, 10, 371-375.

Jensen, A. (1985). Methodological and statistical techniques for the chronometric study of mental abilities. In C.R. Reynolds & V.L. Willson (Eds.), Methodological and statistical advances in the study of individual differences. New York: Plenum Press.

John, E.R., Prichep, L., Ahn, H., Easton, P., Fridman, J., & Kaye, H. (1983). Neurometric evaluation of cognitive dysfunctions and neurological disorders in children. Progress in Neurobiology, 21, 239-290.

Kelly, R.T., Greitzer, F.L., & Hershman, R.L. (1981). Air defense: A computer game for research in human performance (NPRDC Tech. Rep. 81-15). San Diego: Navy Personnel Research and Development Center.

Kinsbourne, M. (1972). Eye and head turning indicates cerebral lateralization. Science, 176, 539-541.

Kinsbourne, M. (Ed.). (1978). Asymmetrical function of the brain. New York: Cambridge University Press.

Knights, R.M., & Bakker, D.J. (1976). The neuropsychology of learning disorders: Theoretical approaches. Baltimore: University Park Press.

Knott, J.R. (1938). Brain potentials during silent and oral reading. Journal of General Psychology, 18, 57-62.

Kooi, K.A., & Bagchi, B.K. (1964). Visual evoked responses in man: Normative data. Annals, New York Academy of Sciences, 112, 254-269.

Kreezer, G. (1937). The dependence of the electro-encephalogram upon intelligence level. Psychological Bulletin, 34, 769-770.

Kreezer, G. (1938). The electro-encephalogram and its use in psychology. American Journal of Psychology, 51, 737-759.

Kreezer, G. (1939). Intelligence level and occipital alpha rhythm in the Mongolian type of mental deficiency. American Journal of Psychology, 52, 503-532.

Kreezer, G., & Smith, F.W. (1936). Electrical potentials of the brain in certain types of mental deficiency. Archives of Neurology and Psychiatry, 36, 1206-1213.

Kreezer, G., & Smith, F.W. (1937). Brain potentials in the heredity type of mental deficiency. Psychological Bulletin, 34, 535-536.

Larson, G.E., & Saccuzzo, D.P. (1986). Jensen's reaction-time experiments: Another look. Intelligence, 10, 231-238.

Lelord, G., Laffont, F., & Jusseaume, P. (1976). Conditioning of evoked potentials in children of differing intelligence. Psychophysiology, 13, 81-85.

Lennox, W.G., Gibbs, E.L., & Gibbs, F.A. (1945). The brain-wave pattern, an hereditary trait. Journal of Heredity, 36, 233-243.

Lewis, G. W. (1979). Visual event related potentials of pilots and navigators. In D. Lehmann & E. Callaway (Eds.), Human evoked potentials. Applications and problems (p. 462). New York: Plenum Press.

Lewis, G.W. (1983a). Event related brain electrical and magnetic activity: Toward predicting on-job performance. International Journal of Neuroscience, 18, 159-182.

Lewis, G.W. (1983b). Bioelectric predictors of personnel performance: A review of relevant research at the Navy Personnel Research and Development Center. (NPRDC Tech. Rep. 84-3). San Diego: Navy Personnel Research and Development Center.

Lewis, G.W. (1984). Temporal stability of multichannel, multimodal ERP recordings. International Journal of Neuroscience, 25, 131-144.

Lewis, G.W., & Blackburn, M.R. (1984). Biomagnetism: Possible new predictor of personnel performance. (NPRDC Tech. Rep. 84-43). San Diego: Navy Personnel Research and Development Center.

Lewis, G.W., Blackburn, M.R., Naitoh, P., & Metcalfe, M. (1985). Few-trial evoked field stability using the DC SQUID. In H. Weinberg, G. Stroink, & T. Katila (Eds.), Biomagnetism: Applications and theory (pp. 343-347). New York: Pergamon Press.

Lewis, G.W., & Froning, J.N. (1981). Sensory interaction, brain activity, and reading ability in young adults. International Journal of Neuroscience, 15, 129-140.

Lewis, G.W., & Rimland, B. (1979). Hemispheric asymmetry as related to pilot and radar intercept officer performance. (NPRDC Tech. Rep. 79-13). San Diego: Navy Personnel Research and Development Center.

Lewis, G.W., & Rimland, B. (1980). Psychobiological measures as predictors of sonar operator performance. (NPRDC Technical Report 80-26). San Diego: Navy Personnel Research and Development Center.

Lewis, G.W., Rimland, B., & Callaway, E. (1976). Psychobiological predictors of success in a Navy remedial reading program. (NPRDC Tech. Rep. 77-13). San Diego: Navy Personnel Research and Development Center.

Lewis, G.W., Rimland, B., & Callaway, E. (1977). Psychobiological correlates of aptitude among Navy recruits. (NPRDC Tech. Note 77-7). San Diego: Navy Personnel Research and Development Center.

Lewis, G.W., Trejo, L.J., Blackburn, M.R., & Blankenship, M.H. (1986). Neuroelectric and neuromagnetic recordings: Possible new predictors of on-job performance. In G.E. Lee (Ed.), Proceedings: Psychology in the Department of Defense. Tenth Symposium (pp. 606-610). Colorado Springs: U.S. Air Force Academy (USAFA TR 86-1).

Lewis, G.W., Trejo, L.J., Nunez, P.L., Weinberg, H., & Naitoh, P. (August 1987). Evoked neuromagnetic fields: Implications for indexing performance. Presented at the 6th International Conference on Biomagnetism, Tokyo, Japan.

Linn, R. (1982). Ability testing: Individual differences, prediction, and differential prediction. In A.K. Wigdor & W.R. Garner (Eds.), Ability testing: Uses, consequences, and controversies. Part II: Documentation Section (pp. 335-388). Washington, DC: National Academy Press.

Lykken, D.T. (1973). The "neural efficiency analyzer" scandal. Contemporary Psychology, 18, 462-463.

Matousek, M., Arvidsson, A., & Friberg, S. (1979). Serial quantitative electroencephalography. Electroencephalography and Clinical Neurophysiology, 47, 614-622.

Mintzberg, H. (1976). Planning on the left side and managing on the right. Harvard Business Review, 54, 49-58.

Mitchell, J.V., Jr. (1985). The ninth mental measurements yearbook. Lincoln, NE: The Buros Institute of Mental Measurement.

Nideffer, R.M. (1977). Test of attentional and interpersonal style. San Diego: Enhanced Performance Associates.

Ornstein, R. (1977). The psychology of consciousness (2nd ed.). New York: Harcourt Brace Jovanovich.

Ornstein, R. (1978). The split and the whole brain. Human Nature, 1, 76-83.

Papanicolaou, A.C., & Johnstone, J. (1984). Probe evoked potentials: Theory, method, and applications. International Journal of Neuroscience, 24, 107-131.

Rhodes, L.E., Dustman, R.E., & Beck, E.C. (1969). The visual evoked response: A comparison of bright and dull children. Electroencephalography and Clinical Neurophysiology, 27, 364-372.

Rubin, M.A. (1938). A variability study of the normal and schizophrenic occipital alpha rhythm. The Journal of Psychology, 6, 325-334.

Saccuzzo, D.P., Larson, G.W., & Rimland, B. (1986). Speed of information processing and individual differences in intelligence. (Tech. Rep. 86-25). San Diego: Navy Personnel Research and Development Center.

Shagass, C. (1972). Evoked brain potentials in psychiatry. New York: Plenum Press.

Shipley, T. (1980). Sensory integration in children: Evoked potentials and intersensory functions in pediatrics and psychology. Springfield: C.C. Thomas.

Shucard, D.W., & Callaway, E. (1973). Relationship between human intelligence and frequency analysis of cortical evoked responses. Perceptual and Motor Skills, 36, 147-151.

Shucard, D.W., & Horn, J.L. (1972). Evoked cortical potentials and measurement of human abilities. Journal of Comparative and Physiological Psychology, 78, 59-68.

Stassen, H.H. (1980). Computerized recognition of persons by EEG spectral patterns. Electroencephalography and Clinical Neurophysiology, 49, 190-194.

Travis, L.E. (1937). Brain potentials and the temporal course of consciousness. Journal of Experimental Psychology, 21, 302-309.

Travis, L.E., & Egan, J.P. (1938). Increase in frequency of the alpha rhythm by verbal stimulation. Journal of Experimental Psychology, 23, 384-393.

Travis, L.E., & Gottlober, A. (1936). Do brain waves have individuality? Science, 84, 532-533.

Travis, L.E., & Gottlober, A. (1937). How consistent are an individual's brain potentials from day to day? Science, 85, 223-224.

Trejo, L.J. (1986). Brain activity during tactical decision-making: I. Hypotheses and experimental design. (Tech. Note No. 71-86-6). San Diego: Navy Personnel Research and Development Center.

Trejo, L.J., Lewis, G.W., & Blankenship, M.H. (1987a). Brain activity during tactical decision-making: II. Probe-evoked potentials and workload. (NPRDC Tech. Note 87-xx, in press). San Diego: Navy Personnel Research and Development Center.

Trejo, L.J., Lewis, G.W., & Blankenship, M.H. (1987b). Brain activity during tactical decision-making: III. Relationships between physiology, simulation performance, and job performance (NPRDC Tech. Note 87-xx, in preparation). San Diego: Navy Personnel Research and Development Center.

Uttal, W.R., & Cook, L. (1964). Systematics of the evoked somatosensory cortical potential: A psychophysical-electrophysiological comparison. Annals of the New York Academy of Sciences, 112, 60-80.

Van Dis, H., Corner, M., Dapper, R., Hanewald, G., & Kok, H. (1979). Individual differences in the human electroencephalogram during quiet wakefulness. Electroencephalography and Clinical Neurophysiology, 47, 87-94.

Vetterli, C.F., & Furedy, J.J. (1985). Evoked potential correlates of intelligence: Some problems with Hendrickson's string measure of evoked potential complexity and error theory of intelligence. International Journal of Psychophysiology, 3, 1-3.

Vineberg, R., & Joyner, J.N. (1982). Prediction of job performance: Review of military studies. (Tech. Rep. No. 82-37). San Diego: Navy Personnel Research and Development Center.

Vogel, W., & Broverman, D.M. (1964). Relationship between EEG and test intelligence: A critical review. Psychological Bulletin, 62 (2), 132-144.

Wasman, M., & Gluck, H. (1975). Recovery functions of somatosensory evoked responses in slow learners. Psychophysiology, 12, 371-376.

Weinberg, H. (1969). Correlation of frequency spectra of averaged visual evoked potentials with verbal intelligence. Nature, 224, 813-815.

Werre, P.F., & Smith, C.J. (1964). Variability of responses evoked by flashes in man. Electroencephalography and Clinical Neurophysiology, 17, 644-652.

Whalen, T. (1984). Decision making under uncertainty with various assumptions about available information. IEEE Transactions on Systems, Man and Cybernetics, SMC-14, 888-900.

Wicke, J.D., Donchin, E., & Lindsley, D.B. (1964). Visual evoked potentials as a function of flash luminance and duration. Science, 146, 83-85.

Wickens, C. (1980). The structure of attentional resources. In R. Nickerson & R. Pew (Eds.), Attention and performance VIII. New Jersey: Erlbaum.

Williams, A.C. (1939). Some psychological correlates of the electroencephalogram. Archives of Psychology, 240, 48.

Wright, G. (1984). Behavioral decision theory. Beverly Hills: Sage Publications.

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