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# The nature of deficits in the rate of information processing after acute mild closed head injury

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City University of New York, 1992

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# THE NATURE OF DEFICITS IN THE RATE OF INFORMATION PROCESSING AFTER ACUTE MILD CLOSED HEAD INJURY

by

Graeme J. Senior

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, the City University of New York.

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# ABSTRACT

## THE NATURE OF DEFICITS IN THE RATE OF INFORMATION PROCESSING AFTER ACUTE MILD CLOSED HEAD INJURY

by

Graeme J. Senior

Adviser: Dr. Doreen Berman

Recent studies have indicated that, following a mild head injury, patients experience slowing in the speed with which they can process information. While standardized tests have often demonstrated this reduction in processing speed, they have proved less useful in identifying the underlying basis of this slowing. Experimental paradigms, such as the memory scanning procedure (Sternberg, 1969a), permit the partitioning of reaction time (RT) into components which reflect the time taken to complete different stages of the task. Two components, the slope and y-intercept, can be derived for those behaviors which are best described by a linear function. For the memory scanning task, the slope estimate reflects the rate at which central comparison processes are made, while the intercept represents the combined time taken to complete sensory-perceptual, decision-making, and response execution processes. The present study used nine variants of the memory scanning procedure to determine the nature of information processing deficits in a group of 13 mild closed head-injured (CHI) patients, by comparing their performance with 13 age-, sex-, education-, and occupation-matched controls. All CHI subjects had experienced a loss of consciousness of less than 20 minutes, had Glasgow

Coma Scale scores on admission of 13 or greater, and were tested within 72 hours of their injury. The first of the nine tasks evaluated the rate at which simple fine motor movements were programmed. The remaining eight tasks, were stimulus matching tests that varied in terms of stimulus type (consonants, numbers, words, and patterns), task complexity, and temporal delay between stimulus and comparison (simultaneous, delayed, subtraction, and categorization). In all the matching tasks, one to four comparison stimuli were presented with a probe stimulus. In the simultaneous identity match conditions, the categorization and subtraction tasks, both probe and comparison set remained on a computer screen until the subject responded. In the delayed conditions, a delay was introduced between stimulus and probe presentations.

All subjects, CHI and not, showed a linear increase in response times as a function of increases in the number of comparison stimuli in a set. Least squares linear regression was used to generate slope and intercept estimates for each subject on each task. Acute mild CHI subjects had significantly steeper slopes than controls on all tasks, suggesting that the slowed rate of information processing is general and not specific to the particular cognitive systems studied. With the exception of the two tasks involving number stimuli, CHI intercept estimates were no different or, in some cases, were faster than those of controls. This indicated that acute mild head injury specifically affected the rate at which central comparison processes were performed and spared the more peripheral sensory, perceptual, decision-making and response execution processes. The implications of these findings for the assessment and cognitive rehabilitation of mild head-injured patients were discussed.

## ACKNOWLEDGEMENTS

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It has been a long road, but one well-travelled, and not soon forgotten!

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# INTRODUCTION

Mild head injury is an extremely common, if not the most common, injury to the central nervous system. Many people experiencing such an injury display no focal neurological abnormalities but complain of a complex of symptoms which include inability to concentrate, memory disturbances, and irritability. These behavioral changes are difficult to demonstrate with standardized neuropsychological tests as many of these tests were developed to detect focal brain damage and are ill-suited for evaluating diffuse effects (Gronwall, 1989).

There is a growing body of evidence to indicate that the cognitive sequelae of mild head injury may result from a reduction in the speed of information processing (Gronwall & Sampson, 1974; Gronwall & Wrightson, 1974; MacFlynn, et al., 1984; Van Zomeren, 1981; Van Zomeren & Deelman, 1976). Information processing approaches, such as the memory scanning paradigm (Sternberg, 1969a), provide an opportunity to examine the underlying nature of this slowing by partitioning mean response times into two components: the slope, which estimates the rate at which central comparison or organizing processes occur; and the intercept, which estimates the time taken to perform the remaining peripheral processes, including sensory-perceptual processing, response selection, and response execution.

The purpose of this study is to evaluate the nature of information processing deficits following mild head injury, using complex reaction time (RT) tasks that were designed to tap different cognitive functions. Comparison of slope and intercept measures for mild head injured patients and control subjects on each of the tasks will indicate the extent to which the slowing experienced by patients is attributable to central versus peripheral cognitive processes. The degree to which differences between the two groups are found on each of the nine tasks will indicate whether this slowing is specific to a particular cognitive system or underlies all of the measured performances.

## Definition and Classification of Mild Closed Head Injury

Head injury encompasses a wide variety of traumas ranging from relatively trivial contusions and lacerations to skull fractures, cerebral contusions, intracranial hematomas, hemorrhages, and infarction. The term "head injury" is, therefore, somewhat misleading, as it is the extent to which the brain has been injured that is of primary concern. Mild or minor head injury, in the absence of known structural damage to the brain, has been defined in terms of Glasgow Coma Scale (GCS) scores, the period of post-traumatic amnesia (PTA) and/or unconsciousness (Binder, 1986). Although these criteria serve as practical indicators of brain injury, they are far from definitive. For example, while the presence of a period of loss of consciousness is an indicator of brain injury, its absence cannot be presumed to indicate the absence of central nervous system dysfunction. The term "head injury" will be used here as it reflects the defining characteristic of the patient group in this study, in so far as we can be certain only that all patients experienced injuries to the head. The use of further criteria serve to increase the likelihood that all the head-injured subjects involved were, in fact, brain injured.

The Glasgow Coma Scale provides a method of estimating severity of injury, using motor, verbal, and eye-opening responses. This scale encompasses the full range of injuries, with scores of 3-8 being termed "severe", 9-12 termed "moderate", and 13-15 termed "minor" (Alves & Jane, 1985). The effectiveness of the GCS for evaluating mild closed head injury has been questioned, however, because of its reliance upon physiological responses. Most patients with mild head injury have recovered consciousness by the time they arrive at the hospital, and are characteristically awake, oriented to their surroundings, and conversing, thereby attaining maximum or near-maximum scores on the scale.

PTA is the period following a head injury which the patient is later unable to remember, and is measured from the time of recovery of consciousness until continuous memory has returned. As long ago as the late 1940s, PTA was proposed as a stable index of severity of injury (Russell & Nathan, 1946). Jennett (1976, 1979) classified the severity of brain injury, utilizing the period of PTA, as: very mild, less than 5 minutes; mild, less than 1 hour; moderate, 1 to 24 hours; severe, 1 to 7 days; very severe, more than 7 days; and extremely severe, more than 4 weeks. PTA is usually assessed through direct questioning of the patient, and the principal criticism of this measure has focused upon the resulting difficulty in obtaining reliable information (Gronwall & Wrightson, 1981; Schachter & Crovitz, 1977). In order to effectively estimate PTA, patients must be able to accurately report the events following their injury, and the examiner must have a sufficiently accurate and independent knowledge of these same events. In the case of mild head injury this is further complicated by the fact that the period of PTA is often extremely brief or non-existent and has often passed by the time an examiner has the opportunity to perform an assessment. Because of this difficulty, the period of loss of consciousness (LOC) has been used as an alternative for PTA, with mild head-injuries associated with periods of unconsciousness of less than 20 minutes (Binder, 1986; Gentilini, et al., 1985; Rimel, Giordani, Barth, Boll, & Jane, 1981; Schoenhuber & Gentilini, 1988). The primary advantage of this measure is that it is relatively easily obtained from reports of witnesses, emergency medical services, or medical staff, and is routinely evaluated as part of the medical work-up.

Despite their limitations, GCS scores and duration of LOC seem to be the most commonly used indicators of severity of injury. Rimel, et al. (1981) and Jagger, Levine, Jane, and Rimel (1984), in their study of admissions to University of Virginia Hospital from 1977 to 1979, used a GCS of 13 to 15, a LOC of 20 minutes or less, and a hospitalization not exceeding 48 hours as their criteria for mild head injury. Kraus et al. (1984), in a study of head injury hospital admissions in San Diego County, used a GCS of 13 to 15 as an indicator of mild injury. On the other hand, Annegers, Grabow, Kurland, and Louis (1980) in their study of head injuries in Olmstead County, Minnesota, defined mild head injury by a duration of LOC or PTA of less than 30 minutes, while Whitman, Coonley-Hoganson, and Desai (1984), in a study of hospital discharges in the Chicago area from 1979 to 1980, classified patients as having mild head injuries if they had a LOC of less than 30 minutes. The Comprehensive Central Nervous System Trauma Centers in San Diego, New York, and Texas use the following criteria for patient eligibility for entry into their minor head injury studies (Marshall & Marshall, 1985): (1) a period of loss of consciousness of less than 20 minutes; (2) neurological abnormalities lasting no more than 48 hours; (3) hospitalization for 48 hours or less with no significant complicating multiple injury; and (4) normal computed tomography (CT) scans.

Whatever criteria are utilized in defining mild head injury, two conditions must be met:

1. The criteria must exclude those patients who have sustained a head injury but not a brain injury. Trauma to the head alone is not a sufficient determination of brain injury; inclusive criteria such as duration of loss of consciousness, period of post-traumatic amnesia, and GCS scores of 13 to 14 are indicative of brain injury (particularly diffuse brain injury).
2. Criteria must also exclude those patients who, despite the apparent

mildness of their trauma, have sustained injuries (to the head or otherwise) that exacerbate either directly or indirectly the effects of the head injury. For example, injuries to the cardiovascular or respiratory systems may compromise oxygen supply to the brain, thus exacerbating the effects of the brain injury. Thus, it is important to exclude those patients with skull fractures, focal injuries (as revealed by neuroimaging techniques), multiple trauma, or significant psychiatric or neurologic histories (especially of prior head injury).

## Epidemiology

The major causes of head injury are traffic and transport accidents, violence, such as assaults, homicides and suicides, and falls (Annegers et al., 1980; Cooper, Tabbador, Hauser, Schulman, Feiner, & Factor, 1983; Jagger et al., 1984; Klauber, Barrett-Connor, Marshall, & Bowers, 1981; Whitman, Coonley-Hoganson, & Desai, 1984). The accurate estimation of the incidence and prevalence of head injuries is complicated by problems with and differences in the criteria for diagnosis of head trauma, methods of case identification, measures of occurrence, and determination of variables of interest. The first national estimates became available in 1974 through the Health Interview Survey of the National Center for Health Statistics (Caveness, 1979). This survey indicated that, annually, 4-5% of the U.S. population sustain head injuries, ranging in severity from lacerations to intracranial injuries.

Defining head injury on the basis of PTA, loss of consciousness, skull fracture or confirmed brain injury, recent studies estimate incidence ranging from 200 to 300 per 100,000 population per year (Annegers, et al., 1980; Cooper et al., 1983; Jagger, et al., 1984; Klauber, et al., 1981; Kraus, et al., 1984; Whitman, Coonley-Hoganson, & Desai, 1984). Frankowski, Annegers, and Whitman (1985) extrapolated these estimates to the total U.S. population and calculated that there are 500,000 new cases of head head injury per year, of which 30%-50% are either moderate, severe, or fatal. Minority populations of major cities have the highest incidence rates (250 to 400 per 100,000), with white populations, and people in small towns and suburban areas, showing the lowest rates (200 per 100,000). The overall incidence rate for individuals aged between 0 and 4 years is approximately 150 per 100,000 and increases to a peak of 550 per 100,000 by age 15 - 24. The incidence then decreases until age 50, after which point it shows an increase with age. Peak incidence for the white population is between ages 15 and 24, while black populations peak between 25 and 40. Males are at twice the risk of females.

The incidence of head injury in other countries does not seem to appreciably differ from that of the United States. The 1977 head injury incidence in New South Wales, Australia, including patients admitted for 24 hour observation, was 380 per 100,000 population, with motor vehicle accidents accounting for 66% of the injuries (McEwin, 1981; Selecki, Simpson, Vanderfield, Ring, &

Sewell, 1980). Males were three times as likely as females to experience head injuries and the peak age for injury was 15 to 24 years. In the United Kingdom, the annual hospital admission rate for head injuries in 1974 was 270 per 100,000 in England and Wales, and 313 per 100,000 in Scotland (Jennett & MacMillian, 1981). Incidence rates of head injuries admitted to Ulleval Hospital in Oslo, Norway from 1964 to 1971 were 266 per 100,000 for males and 101 per 100,000 for females, with the peak age of injury between 15 and 19 years (Kollevold, 1976). In Canada the data is less complete, but studies conducted in Vancouver from 1967 through 1969 indicated that males were twice as likely to sustain head injuries as females, with 75% of adult injuries resulting from motor vehicle accidents and 75% of child injuries accounted for by falls (Klonoff, 1971; Klonoff & Thompson, 1969).

With regard to minor head injuries, it is difficult to estimate the incidence or prevalence because of the great variation in admission practices, the large number of head injuries in which only head lacerations and contusions are sustained, and the fact that many people with mild head injuries do not seek treatment. It appears, however, that the epidemiologic factors underlying mild head injury are the same as those for all head injuries: a predominantly male condition that affects primarily young adults and the elderly, and is most commonly caused by motor vehicle accidents, falls, and violence (Annegers & Kurland, 1979; Jagger, et al., 1984; Klauber, et al., 1981; Kraus, 1980).

## Neuropathological Changes Following Mild Head Injury

Little is known concerning the neuroanatomical changes associated with mild head trauma in humans. The few reports of pathological changes following mild head injury, those of Oppenheimer (1968), Peerless and Rewcastle (1967), and Tomlinson (1970), have been limited to cases of patients who died from complications unrelated to their injury. These investigators described limited axonal damage, primarily within the brainstem, in the form of demyelination, microglial proliferation, and the expulsion of balls of axoplasm (retraction balls).

The shear and tensile forces associated with a mild head injury have been assumed to be similar to those following severe head injury, which physically tear axons, producing a reactive axonal swelling and causing axonal retraction balls (Genarelli et al, 1982; Strich, 1961). If this were the case, it would suggest that even in minor head injury there is immediate and irrevocable axonal damage.

In recent years two animal models of head injury have gained acceptance, the fluid-percussion model in cats (Povlishock, Becker, Miller, Jemkins, & Dietrich,1979; Povlishock, Becker, Cheng, & Vaughan, 1983); and the angular acceleration model in primates (Jane, Steward, & Gennarelli, 1985), have replicated many of the neural changes found in humans following severe and moderate head-injury, and have clarifed our understanding of the pathological changes following mild head injury. These models indicate axonal changes in brainstem areas, particularly the reticular formation, giving support to the proposals of Foltz & Schmidt (1956) and Ward (1966) that the reticular formation is the site of dysfunction in concussion.

Jane, Steward, and Gennarelli (1985), using the primate model, found axon terminal and preterminal degeneration within the brainstem following even mild head injury. Changes in the reticular formation have also been found by Bakay, Lee, Lee, and Peng (1977) in rats following a transient loss of consciousness induced by a blow to the occipital protuberance. Studies using the cat fluid-percussion model have also found axonal changes confined to the brainstem (Povlishock & Kontos, 1985; Povlishock & Becker, 1985), particularly in the ipsilateral cerebral peduncle, ipsilateral basal pons, decussation of the brachium conjunctivum, the ipsilateral red and vestibular nuclei and bilaterally in the reticular core (Povlishock et al, 1983). The genesis of the reactive swelling and retraction balls, however, involved progressive changes rather than an immediate tearing of the axon, with proximal swelling resulting in detachment from the distal swelling within 12 to 24 hours. This finding is supported by Pilz (1983) who did not find retraction balls in humans following head injury until 12 hours post-injury. Povlishock (1986) found that, while focal axonal changes were a consistent feature of experimentally-induced mild head injury, the surrounding vascular and parenchymal tissue showed no structural abnormalities.

Whatever the factors responsible for axonal damage, it appears that mild head injury preferentially affects long-tract decussating axons in the brainstem, without tearing the axon itself or structurally damaging surrounding vascular and parenchymal tissues. Because of its orientation on the neuraxis, the brainstem is particularly vulnerable to the rotational forces commonly generated during head trauma. Povlishock & Coburn (1989) argue that stretching or compression of the axons are the most likely mechanisms, as these would target long-tract axons along the neuraxis and have their greatest effects at focal points along the axons' length. They noted that, due to their isolated and focal nature, the axonal changes are likely to be the sole determinants of subsequent morbidity. As the development of retraction balls is a progressive process, however, the axonal changes may, in fact, be reversible. It should be noted that the degeneration produced by mild injury, although extensive, is still relatively diffuse and not all of the axonal projections of a given system are destroyed (Jane et al., 1985).

## Immediate Neurobehavioral Sequelae of Mild Head Injury

Patients with mild concussion tested for recent memory between 4 and 24 days post-injury showed no differences from control subjects for immediate presentation or after a 3-hour delay for tests of story recall, figure recognition, or verbal paired-associate learning. Significant differences were found only for the Benton Visual Retention Test, a figure recall task (Cronholm and Johnson, 1958).

Mild and severe head-injured patients tested three days after their injury showed significant deficits compared with controls on tests of distractibility and recent memory (McLean, Temkin, Dikmen, & Wyler, 1983). In a three center study, verbal learning deficits were demonstrated in mild head injured patients evaluated with the Selective Reminding Test within one week of injury (Levin, et al., 1987).

Deficits have also been found in patients with mild head-injuries tested within 48 hours of their injury on the Paced Auditory Serial Addition Task (PASAT), a task involving the sequential addition of single-digit numbers presented at progressively faster rates (Gronwall & Sampson, 1974; Gronwall & Wrightson, 1974). The task is complicated by the fact that subjects must respond with the sum of adjacent numbers rather than maintaining a running total. For example, if the first four numbers were 4, 8, 2, and 6, correct responses would be 12, 10, and 8. This requires effective tracking of each digit in immediate memory, the addition of the two numbers, and the inhibition of the tendency to add subsequent numbers to this total. Head-injured patients show greater decline in performance with increased rates of presentation than normals, but the cause of this difficulty is unclear.

Waddell & Gronwall (1984) tested sensitivity to light and sound in patients with minor head injuries (PTA<1 hour), within 7 to 19 days post-injury. They demonstrated increased sensitivity to light, reporting discomfort from a mean light intensity of 1366 lux, when compared with controls matched for age, sex, race, and socioeconomic status, who reported discomfort at a mean of 1783 lux. While the mean differences in discomfort sensitivity to sound intensity (82 dB for CHI vs. 94 dB for Controls) were in the predicted direction, they failed to reach statistical significance.

## Reaction Time and Head Injury

Individual differences in response times have been of concern in the measurement of mental processes since the dismissal in 1795 of the assistant of Nicholas Maskelyne, the royal astronomer of England, for repeated mistakes in the observation of star movements across the sky (Schultz & Schultz, 1987). The application of chronometric methods to the study of brain damage, however, did not become popular until after World War 1. In the early 1920's, reaction time measures were used in a number of studies of patients with post-encephalitic Parkinsonism to evaluate the basis of the observed behavioral slowing. These patients demonstrated slowed response times on simple, choice, and verbal-association reaction time tasks, which was interpreted as indicating slowed mentation rather than retardation of movement alone (Benton,1986). This finding of slowed response times has become one of the most reliable findings in the neuropsychology of brain damage (Milner, 1986).

Complex reaction time procedures have, in general, proved to be more sensitive indicators of cerebral dysfunction than simple reaction time. Benton

(1986) has referred to this phenomenon as the 'complexity hypothesis'. Although studies of brain-damaged individuals comparing two-choice RT with simple RT have failed to demonstrate the superiority of the former procedure (Bruhn & Parsons, 1971; Dee & Van Allen, 1971; De Renzi & Faglioni, 1967), complex RT tasks involving three or more choices have shown greater sensitivity than simple RT (Miller, 1970; Norrman & Svahn, 1961; Van Zomeren, 1981; Van Zomeren & Deelman, 1978). While these studies involved only patients with severe closed head injuries, the complexity hypothesis has also been supported in studies of aging (Anders, Fozard, & Lillyquist, 1972; Dirken, 1972; Eriksen, Hamlin, & Day, 1973), aphasia (Carson, Carson, & Tikovsky, 1968), and dementia (Ferris, Crook, Sathananthan, & Gershon, 1976; Pirozzolo et al., 1981).

### The Memory Scanning Procedure

Over the last twenty years, the item-recognition or memory scanning paradigm (Sternberg, 1969a) has become the standard method for evaluating rate of information processing deficits in clinical populations. The procedure involves the presentation of a set of stimuli to be memorized by the subject. These stimuli are drawn from a pool of possible test items and are defined as the positive set. The remaining stimuli from the test item pool form the negative set. When a test stimulus is presented, the subject is asked to indicate whether it is a member of the positive set by pressing one of two buttons. If the test stimulus is judged not to be a member of the positive set, this is indicated by pressing the other button. Most studies have varied the size of the positive set while keeping equal the likelihood of a test stimulus being a member of the positive or negative set. The mean RT measured from the onset of the test stimulus to the execution of a button-press is characteristically plotted as a function of the size of the positive set. There are two commonly utilized variants of this paradigm: the varied-set and fixed-set procedures. In the varied-set procedure a new positive set is memorized on each trial, while in the fixed-set procedure the same positive set is used for a series of trials. With either approach, four features of the results with normal adults can be noted (Sternberg, 1975):

1. Increases in the size of the positive set result in linear increases in RT.
2. The rate of increase in RT with increasing set size is the same for positive and negative responses. When numbers or letters are used as stimuli, the rate of increase is characteristically 38 msec/item.
3. The y-intercept interpolated from positive responses is about 400 msec.
4. When response types are equiprobable, positive responses are made approximately 40 msecs faster than negative responses.

Sternberg (1969b) has proposed that task performance involves a number of serial stages which can be identified and enumerated through additive factor methodology. This method is based on the assumption that RT can be decomposed into a number of stochastically independent stages, the influences of which can be assessed using analysis of variance.

Pieters (1983) described four properties for these stages: (1) for any input, output is unaffected by factors that influence its duration; (2) each stage is a functional entity that is qualitatively and psychologically different from other stages; (3) each stage can process only one signal at a time; (4) stage durations are stochastically independent. Sternberg (1969a) postulated four stages for his item-recognition task (Figure 1): stimulus encoding, serial comparison, binary decision, and translation and response organization.

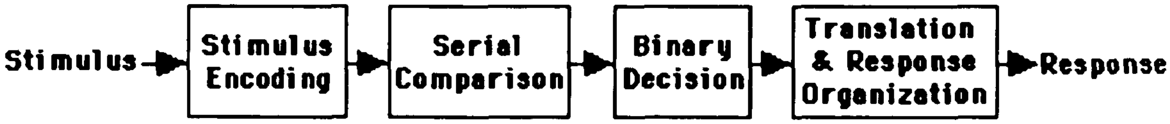


Figure 1. Sternberg's stage model of item recognition

In the memory scanning task, the slope of the RT function reflects those aspects of the task which change systematically with increases in the size of the positive set and is a measure of the rate at which serial comparison processes in active memory are made. The slope has thus been used as a measure of the rate of information processing. The intercept estimate of the RT function reflects those aspects of the task which are common to all trials. Sternberg included stimulus encoding, binary decision, translation, and response organization as stages encompassed by this measure. Sanders (1980), based upon a review of the RT literature, increased the number of stages to six: stimulus preprocessing, feature extraction, identification, response choice, response programming, and motor adjustment, essentially dividing Sternberg's first and last stages into two distinct stages.

The memory scanning procedure has proved useful in documenting cognitive slowing in a wide variety of disorders. Clinical populations demonstrating slowing of the rate of information processing as estimated by slope measures include: Patients with Parkinson's disease (Wilson, Kazniak, Klawans, & Garron, 1980); aphasics (Swinney & Taylor, 1971; Warren, Hubbard, & Knox, 1977); retarded subjects (Dugas & Kellas, 1974; Harris & Fleer, 1974; Maisto & Jerome, 1977; Merrill, 1985; Mosley, 1985; Phillips & Nettlebeck, 1984); normal subjects taking benzodiazepine hypnotics or barbiturates (Subhan & Hindmarch, 1984; Williams, Rundell, & Landgrave, 1981); alcoholics (Mohs, Tinklenberg, Roth, & Kopell, 1979); Korsakoff patients (Naus, Laird, Cermak, & De Luca, 1977); patients with Friedrich's ataxia (Hart, Kwentus, Leshner, & Frazier, 1985); multiple sclerosis (Rao, St. Aubin-Faubert, & Leo, 1989); or HIV infection (Hart, Wade, Klinger, & Hamer, 1990).

Clinical populations for which only intercept differences from normal controls have been found include: Paranoid and non-paranoid schizophrenics (Highgate-Maynard & Neufeld, 1986; Koh, Szoc, & Peterson, 1977; Marusarz & Koh, 1980; Neufeld, 1977; Wishner, Stein, & Paestrel, 1978); cultural-familially retarded children (Silverman, 1974); and patients with affective disorders (Koh & Wolpert, 1983).

Many researchers have suggested that the etiology of this slowed rate of information processing is damage to white matter. Hart, Kwentus, Leshner, and Frazier (1985) have associated slowed rates of information processing with subcortical deficits in a depressed sample, while Rao, Leo, Haughton, St. Aubin-Faubert, and Bernardin (1989) implicated diminished corpus callosum capacity in patients with multiple sclerosis. Closed head injury is frequently associated with diffuse axonal injury attributed to shearing forces, and Wilson, Wiedmann, Hadley, Condon, Teasdale, and Brooks (1988), using magnetic resonance imaging, have proposed that deep structure abnormalities are responsible for the slowed rates of information processing in these patients.

## Head Injury and the Rate of information Processing

Senior and Tweedy (1984,1986) evaluated mild head-injured adults within 48 hours of their injury and again after one month, using a letter memory scanning task. Head-injured patients at initial testing demonstrated significantly slower scanning rates than controls. This was interpreted as reflecting the vulnerability of central comparison processes to head injury, while the lack of a significant intercept difference between the two groups reflected the relative integrity of sensory-perceptual, decision-making, and output processes. One month after injury, the between-group differences were no longer significant.

Haut, Petros, Frank, and Lamberty (1990) compared the performance on measures of short-term memory of twelve severe closed head-injured patients (loss of consciousness greater than five days) one year or more post-injury with normal matched controls. Significant differences were found between the groups on a letter memory scanning task, indicating that the severely head-injured subjects responded more slowly than did controls. The CHI group had both significantly greater mean slope and intercept values.

Shum, McFarland, Bain, and Humphreys (1990) employed Sternberg's additive factor methodology (Sternberg, 1969b) to evaluate the impact of CHI upon four information processing stages: feature extraction, identification, response selection, and motor adjustment, as measured by signal quality, signal similarity, signal-response compatibility, and foreperiod uncertainty, respectively. This study utilized a visuospatial four-choice reaction time task in which subjects were required to press the response button indicated by the direction of an arrow. Head-injured subjects were divided into three groups: mild (GCS>13); chronic severe (GCS<9, >1 year post-injury); and subacute severe (GCS<9, <1 year post-injury). As all variables served to function additively with respect to overall RT, the authors argued that a sequential model of information processing with four independent stages adequately described patient and control group performance. Comparisons across head-injured groups suggested that severe CHI patients in the subacute phase were impaired on identification and response selection and that the difficulty with identification diminished with time, leaving impairment on only the response selection stage during the chronic phase. The mild head-injured group showed no deficits in any of the four inferred stages.

These studies indicate that mild CHI patients experience a slowing in the rate of central comparisons with relative sparing of the speed of sensory-perceptual, decision-making, and output processes. These latter components are not insensitive to severe head-injury but do not seem vulnerable to milder insults. A question that has not been addressed in this regard is the relative specificity of this effect. The slowed comparison processes in CHI may be viewed either as being specific to the accessing of the memory system in the memory scanning task, or as a reflection of a general slowing of all rate-related processes. If the slowing is specific to the memory system, then delayed identity-matching tasks such as the memory scanning procedure would demonstrate slowed rates of processing as estimated by slope functions, while simultaneous identity-matching tasks would show no slope differences between head-injured and control subjects. If, however, slowed scanning rates are a manifestation of a general diminution in the rate of information processing, all rate-related tasks should demonstrate differences in response times between head-injured and control subjects. Furthermore, if slowing is attributable to trauma-induced changes in some central rate-maintaining mechanism, then greater task complexity should result in greater slowing in response times.

## Rationale

The current study sought to assess the relative impact of acute mild head injury upon the rate of information processing in a number of different cognitive systems by evaluating acute mild closed head-injured and normal subjects on nine reaction time tasks. Consonants, numbers, words, and patterns were used in eight tasks for visual identity-matching with comparison sets of stimuli. Two of these tasks presented consonant and pattern stimuli for delayed identity-matching with previously learned comparison sets. Two tasks used words and numbers to evaluate speed of processing for subtraction and categorization transformations. These four tasks were matched with four control conditions that were identical to the tasks above except that the stimuli (consonants, patterns, numbers, and words) were presented for simultaneous matching with comparison sets. A ninth task utilized a simple reaction time procedure to evaluate the influence of different lengths of motor sequences on the rate at which these sequences are programmed.

If slowing in the rate of central comparison processes in CHI subjects is specific to the memory scanning procedure then such subjects should demonstrate significant slope increases relative to controls on delayed identity-match tasks. Alternatively, if a general mechanism is responsible for this slowing, any delayed or simultaneous task would be expected to show significant between-group slope differences. Furthermore, the degree of slowing should be predicted, in part, by the level of complexity of the task involved. Transformation tasks should produce greater slope differences than delayed identity-matching which in turn should produce greater differences than simultaneous identity-matching. The cognitive aspect of the motor response itself was assessed using a task which varied motor sequence lengths. The size of between-group differences for intercept measures would indicate the extent to which sensory-perceptual, decision-making, and output processes are rendered vulnerable to the effects of mild head injury.

## Hypotheses

1. Acute mild closed head injury produces slowed reaction times: mean response times on all tasks for mild CHI subjects will be significantly greater than those of control subjects.

2. The slowed reaction times found following acute mild closed head injury are a result of an increase in the rate of central comparison processes: slope estimates of mild CHI subjects will be significantly greater than those of control subjects on each task.

3. Acute mild closed head injury spares peripheral stages such as sensory-perceptual, response selection, and response execution: no significant differences will be found between the intercept estimates of the mild CHI and control subjects on each task.

4. The slowing in the rate of information processing following acute mild closed head injury is general, and not specific to a particular cognitive system: significant between-group differences in slope estimates will be found on all tasks.

# METHOD

## Subjects

Subjects were 13 mild closed head-injured (CHI) patients (4 females; 9 males) and 13 matched controls, all aged between 18 and 37 years. The patient group was comprised of consecutive admissions for mild head injury to the Emergency Room of the City Hospital Center at Elmhurst, New York who were subsequently transferred to the Department of Neurosurgery for observation and evaluation. Each had experienced a documented loss of consciousness of less than 20 minutes as a result of their injury and were tested within 72 hours of admission. Patients were excluded from the study if they were under the influence of drugs and/or alcohol at the time of examination or had one or more of the following: a Glasgow Coma Scale rating on admission of less than 13; x-ray evidence of skull fracture; CT or MRI evidence of focal brain lesion; history of neurologic or psychiatric dysfunction. Loss of consciousness and coma scale criteria were used for classifying the head injury as mild because of their common usage and consistent determination at the time of hospital admission. X-ray evidence of skull fracture, although not uncommon in mild head injury, led to patient exclusion as more severe brain injury could not be ruled out. Similarly, CT or MRI evidence of focal injury would suggest a level of injury severity beyond the mild range. Subjects with prior neurological or psychiatric histories or those under the influence of medications at the time of testing were also excluded to minimize the confounding effects of these conditions upon RT.

Control subjects were volunteers from the New York City area who worked in similar occupational settings to the patients in the study. These subjects were recruited by seeking volunteers from similar work-sites, or through association (friends or colleagues) with a head-injured subject. They were matched subject-by-subject with the mild CHI patients for age, sex, years of education, and occupation. No control subject had a history of neurological or psychiatric dysfunction or used medications at the time of testing. The demographic characteristics of the control and CHI subjects are described in Table 1.

## Procedure

Each experimental session involved the presentation of nine tasks. Each task, (see Table 2) was designed to evaluate the rate of information processing for a different task demand (motor output, discrimination, working memory, subtraction, or categorization) and stimulus condition (consonants, numbers, words, or patterns). The matching tasks (2 through 9) were based on a paradigm in which trials consist of comparing a probe stimulus with a set of comparison stimuli. The Simultaneous Identity-Matching tasks were designed to serve as control conditions for the Delayed and Transformation tasks. The control tasks were identical to their Delayed and Transformation counterparts except that the probe and comparison stimuli appeared concurrently on the

Table 1. Subject Demographic Data

| | Closed Head Injured Subjects | | | | | Control Subjects | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Age (yrs.) | Sex | Educat. (yrs.) | Occup.* Class | Trauma | | Age (yrs.) | Sex | Educat. (yrs.) | Occup. Class |
| CHI 1. | 21 | Male | 15 | 6 | Assault | N 14. | 21 | Male | 15 | 6 |
| CHI 2. | 25 | Female | 16 | 1 | MVA | N 15. | 25 | Female | 16 | 1 |
| CHI 3. | 31 | Male | 12 | 3 | Fall | N 16. | 31 | Male | 12 | 3 |
| CHI 4. | 18 | Male | 12 | 6 | Assault | N 17. | 18 | Male | 12 | 6 |
| CHI 5. | 37 | Male | 10 | 2 | MVA | N 18. | 35 | Male | 10 | 2 |
| CHI 6. | 25 | Male | 12 | 5 | Fall | N 19. | 25 | Male | 12 | 5 |
| CHI 7. | 31 | Female | 12 | 4 | MVA | N 20. | 31 | Female | 12 | 4 |
| CHI 8. | 19 | Female | 13 | 6 | Fall | N 21. | 19 | Female | 13 | 6 |
| CHI 9. | 23 | Male | 12 | 2 | Assault | N 22. | 23 | Male | 12 | 2 |
| CHI 10. | 19 | Male | 13 | 6 | Assault | N 23. | 19 | Male | 13 | 6 |
| CHI 11. | 19 | Male | 13 | 6 | Assault | N 24. | 19 | Male | 13 | 6 |
| CHI 12. | 22 | Female | 12 | 4 | Assault | N 25. | 22 | Female | 12 | 4 |
| CHI 13. | 28 | Male | 14 | 4 | MVA | N 26. | 28 | Male | 14 | 4 |
| Mn | 24.46 | | 12.77 | | | | 24.30 | | 12.77 | |
| SD | 5.82 | | 1.54 | | | | 5.48 | | 1.54 | |

* Occupational Classes:

1 = Professional & technical workers
2 = Managers, clerical & sales workers
3 = Craftsmen and foremen
4 = Operatives, service workers
5 = Laborers
6 = Students

screen and subjects were to determine whether or not probes matched items in the comparison set. Delayed Identity-Match tasks involved presentation of probe trials after some delay following offset of the comparison stimuli. The Transformation tasks involved concurrent probe and comparison stimuli but required subjects to transform the probe in some way, i.e. categorization or subtraction. These tasks shared identical motor output requirements in the form

Table 2. Tasks identified by abbreviation, stimulus used, and primary cognitive process assessed.

| Task | Abbreviation | Stimulus | Process |
|---|---|---|---|
| 1. Motor programming | Motor | Star | Motor program |
| Simultaneous Identity-Matches | | | |
| 2. Consonant | Consonant SIM | Consonant | Visual Discrimination |
| 3. Pattern | Pattern SIM | Pattern | Visual Discrimination |
| 4. Number | Number SIM | Number | Visual Discrimination |
| 5. Word | Word SIM | Word | Visual Discrimination |
| Delayed Identity-Matches | | | |
| 6. Consonant | Consonant DIM | Consonant | Working Memory |
| 7. Pattern | Pattern DIM | Pattern | Working Memory |
| Transformation Matches | | | |
| 8. Subtraction Identity | Subtraction | Number | Arithmetic |
| 9. Class Exemplar Categorization | Categorization | Word | Semantic processing |

of pressing "Yes" or "No" keys, while the Motor Programming task involved changes in the complexity of the subjects' motor output.

Figure 2 presents the template upon which the flow charts for the nine tasks are based (figures 3 through 7). The components which are unique to each flow chart are surrounded with darkened borders to contrast them with those which are shared by all flow charts (i.e. the template). As the template indicates all tasks include a tone presentation to initiate each block of trials, the presentation of probe stimulus (a cue stimulus in the case of the Motor task), and some form of response made by the subject. This cycle is continued until all trials within each set size block have been presented.

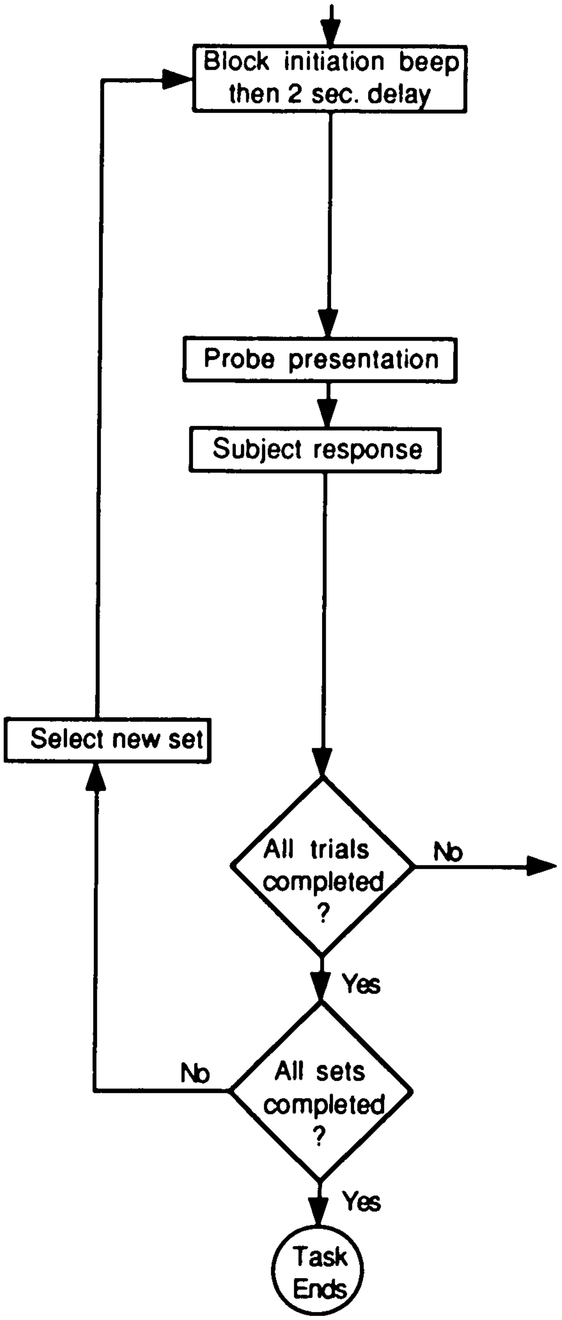


Figure 2. Template for task flow charts.

## Motor Programming Task

In this task (see Fig. 3), subjects were taught three key-press sequences or sets. Unlike the other tasks, three fingers and three keys were utilized. Subjects placed the index, middle, and ring fingers of their preferred hand on three specified computer keys: "J", "K", and "L" for the right hand; "S", "D", and "F" for the left hand. The one-key-press was executed with the index finger (e.g."J"); the two-key-press sequence was executed with the index finger followed by the ring finger (e.g. "J" then "L"); and the three-key-press sequence was executed with the index finger, followed by the ring finger and then the middle finger (e.g. "J" then "L" then "K"). Each key-press sequence was demonstrated to the subject, followed by the performance of ten practice trials. Experimental trials consisted of the subject executing the required key-press sequence each time a star cue appeared, until 45 correct trials had been completed. Each block of practice and experimental trials was followed by the demonstration and testing of the next key-press sequence until all three sequences had been completed. Reaction times, measured from the onset of the star cue until the execution of the first key-press in each sequence (i.e. the "J" key), were recorded for each trial.

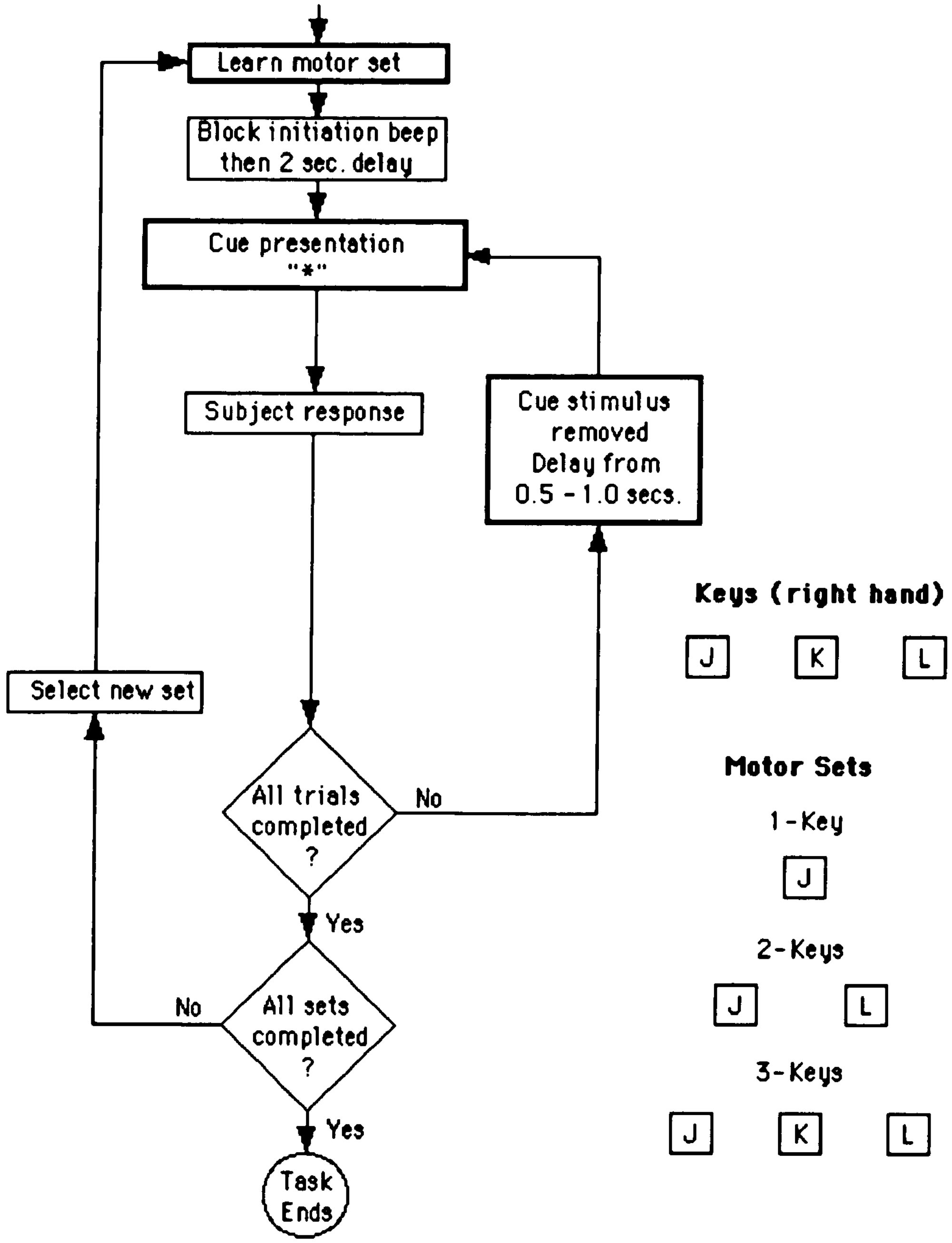


Figure 3. Flow chart for the motor programming task.

## General Procedures for Other Tasks

The following general procedures applied to all tasks except Motor Programming. The top third of the monitor screen contained a centrally delineated set area in which comparison sets were displayed. The size of the set area changed from task to task depending upon the size of the stimuli, but remained constant during each task. The middle third of the screen displayed a smaller delineated probe area located centrally, in which probe items were presented. The size and location of the probe area remained unchanged throughout the experiment.

Each task consisted of four blocks of 24 trials each, with each block beginning with the presentation of a new comparison set. Comparison sets varied in size from one to four stimuli. For the delayed identity-match tasks these sets were removed prior to probe presentation, but for all other tasks they remained on the screen. The beginning of each block was signalled by a 1,000 Hz warning tone of one second duration, followed by a 2 second delay. On each trial a probe stimulus was presented and remained visible until the subject made a response. Subjects rested the index and middle fingers of their preferred hand on two adjacent keys on the keyboard: "N" and "M" for right-hand preferred subjects; and "C" and "V" for left-hand preferred subjects. These served as "yes" and "no" response keys with the left of the two keys indicating a "yes" response and the right key indicating a "no" response. There was an intertrial interval, randomly varied from 0.5 to 1 second, to inhibit subjects from developing a rhythmic pattern of responding. A 30 second interval intervened between blocks of trials. Subjects were required on each trial to indicate whether or not the probe was a member of the comparison set by pressing the "yes" or "no" key. Subjects were instructed to respond upon probe presentation "as quickly as possible without making any errors" (See Appendix A for subject instructions) and "yes" or "no" responses were correct equally often. Choice reaction times, measured in milliseconds from the onset of the probe stimulus to the execution of the key-press, were recorded by the computer for each trial. Individual key-presses were recorded to permit later generation of accuracy and error scores.

Subjects performed two practice blocks, each of ten trials, at the beginning of each task to familiarize them with task requirements. Practice blocks utilized comparison sets of size one and three with probes drawn from stimuli that had not been included in the experimental set pools. In all other respects, practice trials were conducted in the same manner as experimental trials. Individual practice blocks were repeated if accuracy was below 90%.

Due to its complex motoric requirements, the Motor Programming Task was performed first by all subjects. The remaining eight tasks were performed in pairs based upon the type of stimulus involved. Thus the two tasks using consonants were presented consecutively, as were the pattern, number, and word tasks. The order of paired tasks and the order of tasks within each pair were randomly determined by computer (Table 3).

Table 3. Examples of task ordering.

| Order | Example 1 | Example 2 | Example 3 | Example 4 |
|---|---|---|---|---|
| 1 | Motor | Motor | Motor | Motor |
| 2 | Consonant DIM | Number SIM | Word SIM | Pattern DIM |
| 3 | Consonant SIM | Subtraction | Categorization | Pattern SIM |
| 4 | Pattern SIM | Consonant SIM | Subtraction | Categorization |
| 5 | Pattern DIM | Consonant DIM | Number SIM | Word SIM |
| 6 | Number SIM | Word SIM | Pattern DIM | Consonant DIM |
| 7 | Subtraction | Categorization | Pattern SIM | Consonant SIM |
| 8 | Categorization | Pattern DIM | Consonant DIM | Number SIM |
| 9 | Word SIM | Pattern SIM | Consonant SIM | Subtraction |

## Simultaneous Identity-Match Tasks

### Consonant; Number; Word; Pattern

For these tasks the comparison set for each block remained present on the screen during probe presentation. Subjects were required to indicate whether or not the probe stimulus was physically the same as any one of the members of the comparison set. The flow of trials for the consonant, word, and pattern tasks are outlined in figure 4 and, except for the stimuli involved, the task demands are identical in all respects. The flow chart figures give examples of comparison set stimuli for a set size of two items, with positive and negative probes for consonant (A), pattern (B), and word (C) stimuli.

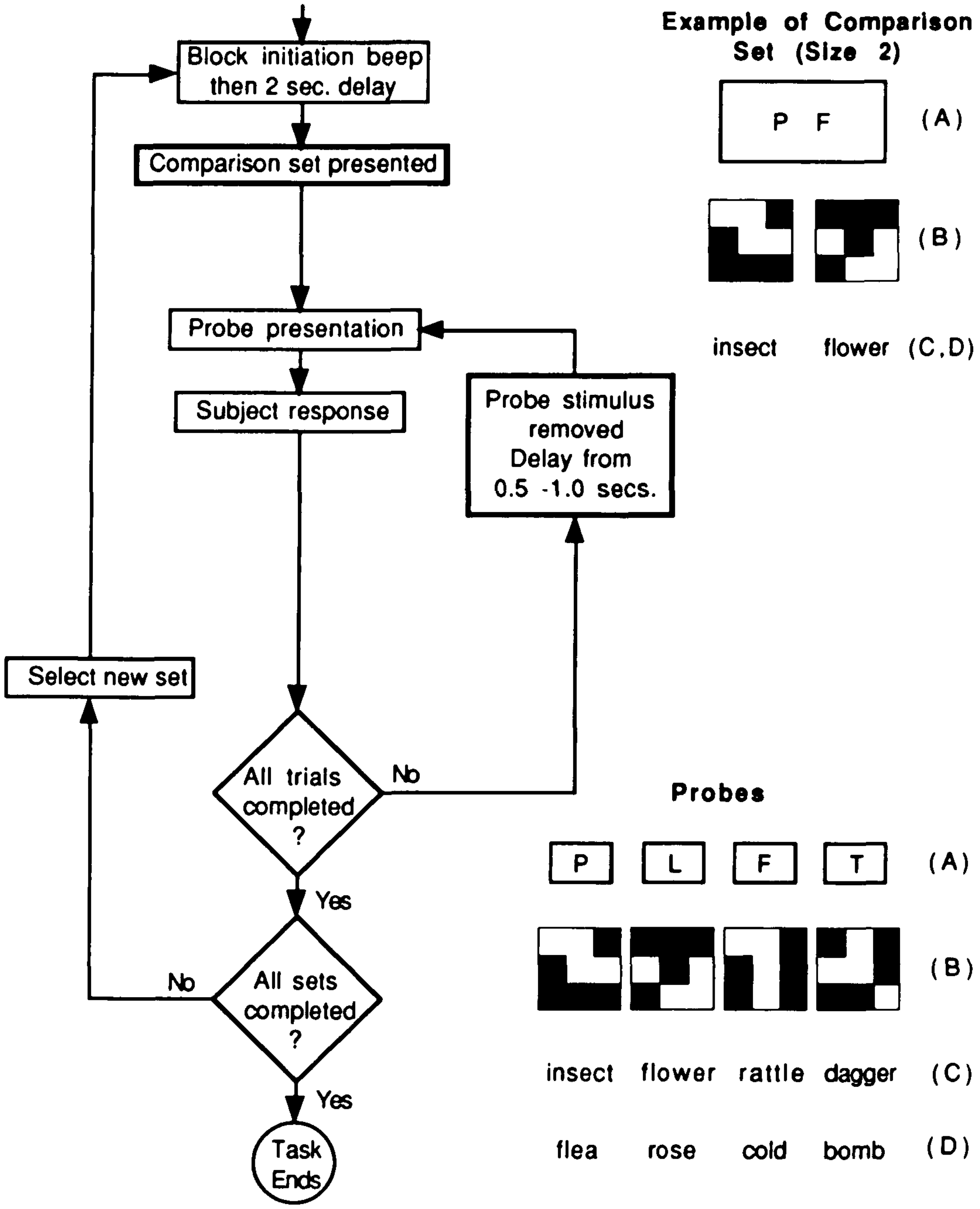


Figure 4. Flow chart for simultaneous identity-match tasks: Consonant (A), Pattern (B), Word (C), and Class exemplar categorization (D).

The number task (Figure 5 A) differed from these others only in that multiple comparison sets were used at each set size. This was necessary in order to keep the two number tasks (Number SIM and Subtraction), as similar as possible. This resulted in the presentation of twelve comparison sets of size one, six sets of size two, four sets of size three, and three sets of size four. Subjects were alerted to changes in the comparison numbers by the set flashing on and off for a period of two seconds prior to the continuation of probe presentation.

## Delayed Identity-Match Tasks

### Consonant

Sternberg's (1969) fixed-set item recognition procedure (see figure 6) was used. Subjects were shown sets of one to four consonants and asked to memorize them. After correctly reciting the memory set both forwards and backwards following its removal, the set area was cleared and a block of 24 trials was performed. Subjects were required to determine whether or not the probe letter was a member of the memorized set. After the completion of each block, a new set was presented for memorization until all four sets had been tested.

### Pattern

This task differed from the delayed consonant task both in its use of pattern stimuli and in the adoption of a varied-set item recognition procedure. In this, the comparison set was presented prior to each trial within the block (figure 7).

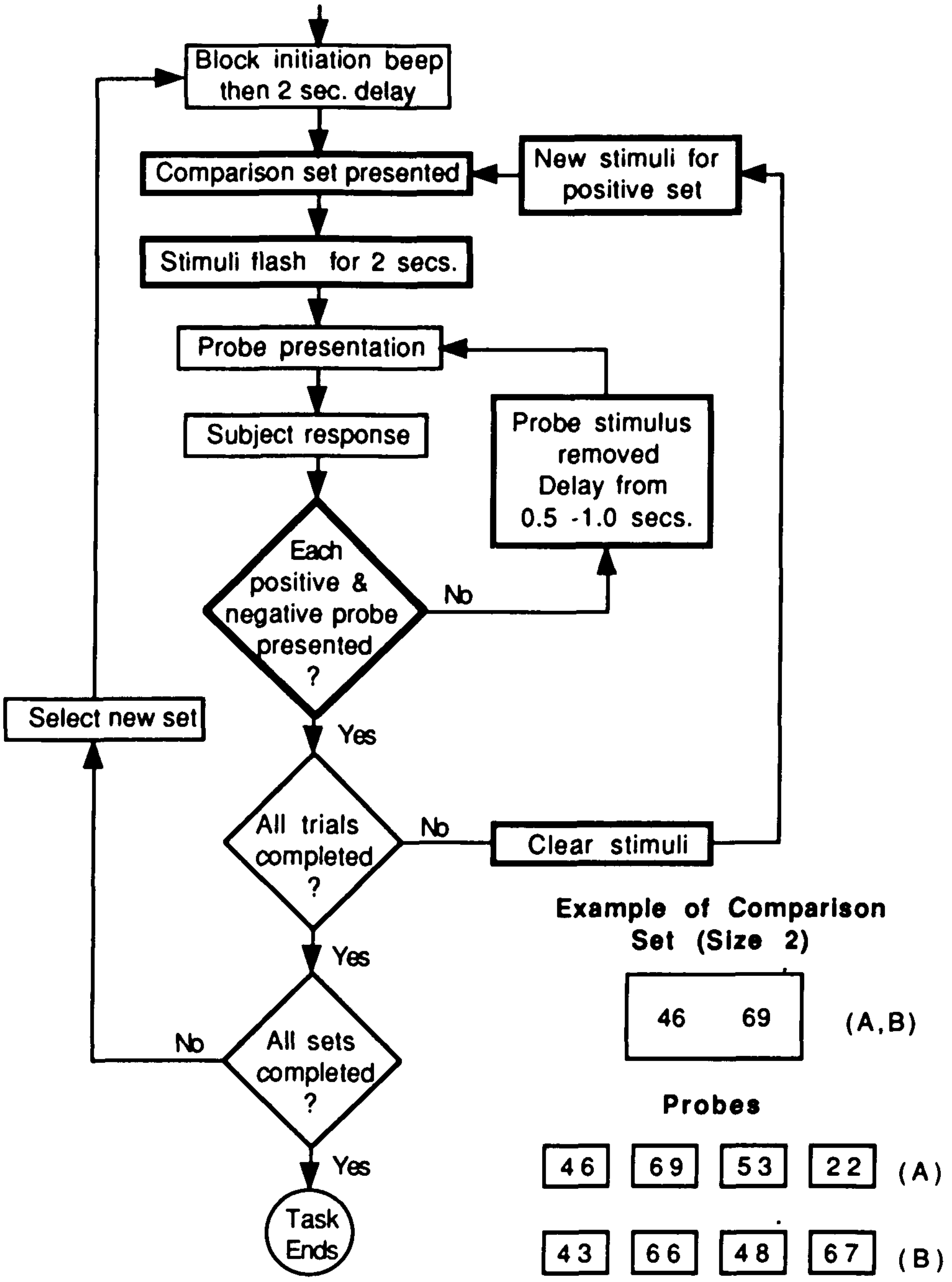


Figure 5. Flow chart for Number simultaneous identity-match (A) and Subtraction identity-match (B).

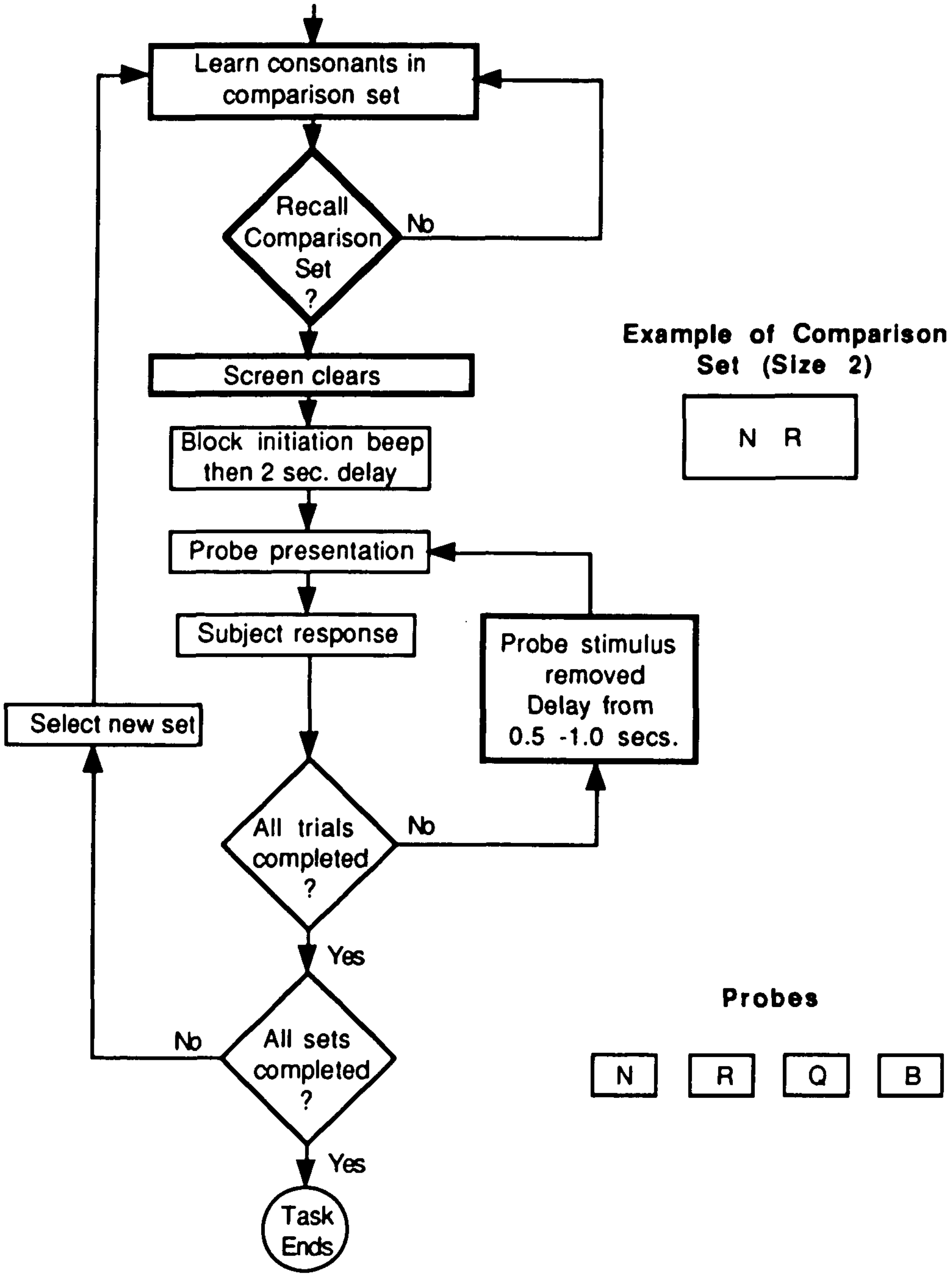


Figure 6. Flow chart for Consonant delayed identity-match task.

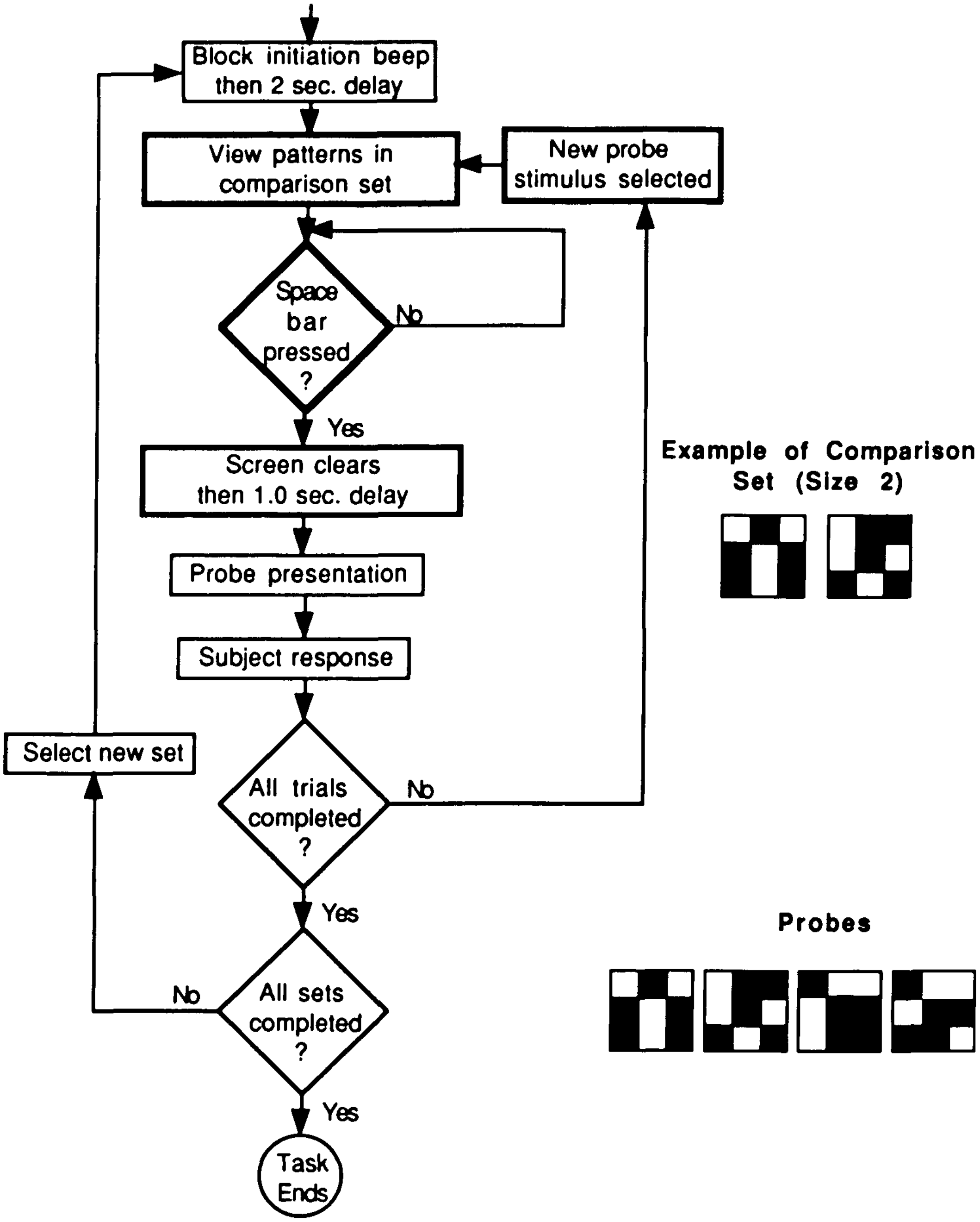


Figure 7. Flow chart for Pattern delayed identity-match task.

Given the complexity of the pattern stimuli and the difficulty in demonstrating adequate learning of the positive set prior to each block, the varied set procedure permitted equivalent exposure of stimuli to all subjects prior to each trial. No differences have been found for mean response times of individuals who have received both the fixed-set and varied-set procedures (Sternberg, 1975). Subjects initiated each trial by pressing the space bar on the keyboard with the non-preferred hand. On this signal, the set area cleared, followed by a one second delay and presentation of a probe.

## Transformation Tasks

### Subtraction Identity-Match

Subjects were presented with comparison sets of two-digit numbers which remained displayed. The subject's task was to indicate whether or not the probe number was three less than any one of the displayed numbers (see figure 5 (B)). To prevent the memorization of correct responses, and thus the execution of an identity-match, the comparison set was changed upon completion of positive and negative probes for each set of values as described for the Number SIM. For example, a comparison set of two numbers, 26 and 54, are displayed on the screen. After two positive probes (23 and 51) and two negative probes (28 and 53) are presented, the comparison set is changed to another two numbers, 77 and 39, which flash for a period of two seconds and are then tested with probes.

### Class Exemplar Categorization

This task was the same as the Word SIM task except that the words in the comparison set represented category names (e.g. animals, fruits), while probe words served as category exemplars (e.g. bear, lime)(see figure 3 D). The subject's task was to indicate whether or not the word was an exemplar of any one of the displayed categories.

## Apparatus and Stimuli

Stimulus ordering, presentation, and data collection were performed using an IBM XT computer equipped with a standard green display monitor. Responses were made on the IBM keyboard. All tasks were programmed using Microsoft Quickbasic, version 4.5.

Stimuli for tasks one through eight were drawn from four pools of visually presented items which consisted of numbers, consonants, words, and patterns. Stimuli were assigned to either a positive comparison set of probes to which a "yes" response should be made, or a negative comparison set to which a "no" response should be made.

### Numbers

Numbers were randomly assigned by computer to positive and negative sets for task 2 (Simultaneous Number) and task 7 (Subtraction) from a pool of 63 two-digit numbers which remained after all two-digit numbers which terminated in 0, 1, and 2 had been removed. These numbers were excluded in order to avoid solutions to the Subtraction Identity-Match task that cross the decade divisions, thereby involving an arithmetic carrying operation.

### Consonants

Twenty one consonants were used as comparison stimuli in tasks 1 and 5 (Simultaneous and Delayed Consonant Identity-Match). Nc vowels were included, in order to reduce the likelihood of generating pronounceable words. Sets of one, two, three, and four consonants were randomly generated by computer. These sets were then examined for the presence of any groupings that resembled words. Such groupings can produce disproportionately fast reaction times. When these were found, the set was rejected and a new set was generated.

### Words

Forty eight words were selected from ten of the 21 categories included in the Howard (1979) category norms, for use as the positive probes for tasks 3 and 8 (Simultaneous Word Identity-Match and Class Exemplar Categorization). A second pool of 48 words drawn from all categories were used as the negative probes. The positive probe words were matched as closely as possible with those of negative probe words for length and category-association. This resulted in each word set containing one 3-letter word, four 4-letter words, three 5-letter words, two 6-letter words, and two 7-letter words. It was necessary to use some stimuli drawn from comparison set categories as negative probe words. However, these words were never used as negative probes where the category was a member of the comparison set. For example, the word "giraffe" (drawn from the category "Animal" used in set size one) is used as a negative probe word for set size two where the comparison set categories are "Insect" and "Flower". The ten categories defining comparison set membership and the words selected as positive and negative probes, with their frequency of association measures, are listed in Appendix B.

### Patterns

A pool of 20 patterns (see Appendix C), each consisting of five filled cells of a 3x3 matrix, were used as stimuli for tasks 4 and 6 (Simultaneous and Delayed Pattern Identity-Match). The stimuli were chosen from a larger pool of randomly generated patterns, based upon their apparent dissimilarity from each other and from easily verbalizable forms.

## Statistical Analysis

Means and standard deviations of response latencies for correct responses to positive and negative probes were computed for each subject. Least squares linear regression was used to fit individual linear functions to the mean responses at each set sizes. Slope and intercept coefficients of these linear functions for each subject were used as the dependent variables in the statistical analyses. For Match tasks, mean slope and intercept estimates were each subjected to a 2 x 2 (Group x Probe) mixed analysis of variance with Probe as a repeated measure. Seven 2 x 2 x 2 (Group x Task x Probe) analyses of variance were performed adding Task as another repeated measure to compare SIM tasks, DIM tasks, Transformation tasks; and each of the SIM tasks with their corresponding DIM or Transformation tasks. Error data analysis was limited to evaluation of between group-differences on each task with dependent T-tests.

# RESULTS

## Analysis of Error Data

Few errors were made by subjects on any of the nine tasks and no significant differences in overall average error rate were found between CHI and normal subjects (2.05% vs. 1.77%). For the CHI group, average error rates ranged from a low of 0.4% on the Motor task to a high of 3.36% on the Number SIM task. Normal subjects ranged from a low rate of 0.23% on the Motor task to a high of 3.29% on the Number SIM task. Due to the general paucity of errors and the lack of between-group differences, no further error analysis was undertaken.

## Analyses of Slope and Intercept Estimates

Prior to the derivation of slope and intercept estimates, mean latencies of all correct responses for all subjects at each comparison set size were evaluated with polynomial tests of order (Systat) to establish that the set size effect was best described by a linear function in each task. The results of these tests are listed in Appendix D. Mean response latencies at each of the comparison set sizes were subjected to least squares linear regression to generate slope and intercept estimates for each subject on each task. These estimates were then separately analysed for each task using analysis of variance (see Appendix E). Of the significant interaction effects included in the appendix, only those which differentiate between the two groups will be described below. Table 4 shows mean slope and intercept estimates for the CHI and normal groups combining data from correct trials for positive and negative probes. The values for slope and intercept estimates in this table deviate slightly from the regression equations displayed in figures 8 through 16. This is because the values in the table are averages of regression components fitted to individual subject mean response times, while the equations displayed in the figures represent best fits to the group mean response times. Slope and intercept estimates for each task can be found in Appendix F.

Table 4. Means of slope and intercept estimates for the mild CHI and normal groups averaged across positive and negative probes.

| | Slope (msec/item) | | | Intercept (msec) | | |
|---|---|---|---|---|---|---|
| Group: | CHI | Normal | p= | CHI | Normal | p= |
| Motor Programming | 136.61 | 61.19 | .023 | 601.56 | 646.81 | .547 |
| Simultaneous Identity-Match | | | | | | |
| Consonant | 78.43 | 33.85 | <.001 | 315.86 | 364.19 | .098 |
| Pattern | 152.85 | 75.94 | .001 | 293.80 | 435.54 | .011 |
| Number | 111.19 | 97.47 | .163* | 401.54 | 259.37 | <.001 |
| Word | 141.64 | 43.95 | .001 | 277.59 | 311.64 | .512 |
| Delayed Identity-Match | | | | | | |
| Consonant | 76.86 | 33.13 | <.001 | 303.15 | 364.64 | .038 |
| Pattern | 104.61 | 66.33 | .001 | 342.75 | 329.05 | .534 |
| Transformation | | | | | | |
| Subtraction | 205.10 | 145.04 | .141* | 797.26 | 328.70 | .011 |
| Categorization 422.33 | 50.09 | <.001 | 363.21 | 500.79 | .188 | |

* Significant slopes differences found for negative probe trials.

### Motor Programming Task (Fig. 8).

#### Slopes

Mean slope estimates were significantly greater (t(24) = 2.50, p=.02) for the CHI group (136.61 msecs/item) than for normals (61.19 msecs/item), indicating that CHI subjects have a slower rate of motor programming than their control counterparts.

#### Intercepts

No significant differences in intercept estimates were found between the two groups, indicating that they do not differ in the time taken to execute the sensory, perceptual, and motor processes involved in this task.

### Simultaneous Identity-Match Tasks (Figs. 9 through 12)

#### Slopes

Mean slope estimates were significantly greater for CHI than normal subjects on each of the Consonant (F(1,24) =22.13, p<.001)(see Figure 9), Word (F(1,24) =15.96, p=.001)(see Figure 11), and Pattern tasks (F(1,24) =14.02, p=.001)(see Figure 12), indicating that on each of these tasks the rates at which CHI subjects perform central comparison processes were significantly slower than those of normal subjects. There was no overall slope difference between the two groups on the Number task, implying equivalent rates of information processing for CHI and normal subjects on this task. However, there was a significant Group x Probe interaction (F(1,24) = 5.11, p=.033), which indicated a slower processing rate for the CHI group than the normal group on negative probe trials (CHI: 140.2 vs. Normal: 111.4 msecs/item) (Fig. 10b) but not for positive probes (CHI: 83.5 vs. Normal: 83.58 msecs/item) (Fig. 10a). Significant Group x Probe interactions were also found on the other simultaneous identity-match tasks, with between-group differences in the rate of central comparison processes greater for positive than negative probe slopes on the Consonant (F(1,24) =4.21, p=.05) and Pattern (F(1,24) =4.51, p=.044) tasks, and negative greater than positive on the Word (F(1,24) =5.45, p=.028) task.

### Intercepts

There were significant differences in intercept estimates between the two groups on the Pattern (F(1,24) =7.50, p=.011) and Number tasks (F(1,24) =18.55, p<.001). While CHI subjects were significantly slower than normals (401.54 vs. 259.37 msecs) in performing sensory-perceptual and motor processes on the Number task, they were significantly faster than control subjects (293.80 vs. 435.54 msecs) on the Pattern task. A significant Group x Probe interaction (F(1,24) =6.41, p=.018) was found for performance on the Consonant task with between-group intercept differences greater for positive (CHI: 278.03 vs. Control: 350.87 msecs) than negative probe trials (CHI: 353.69 vs. Control: 377.51 msecs).

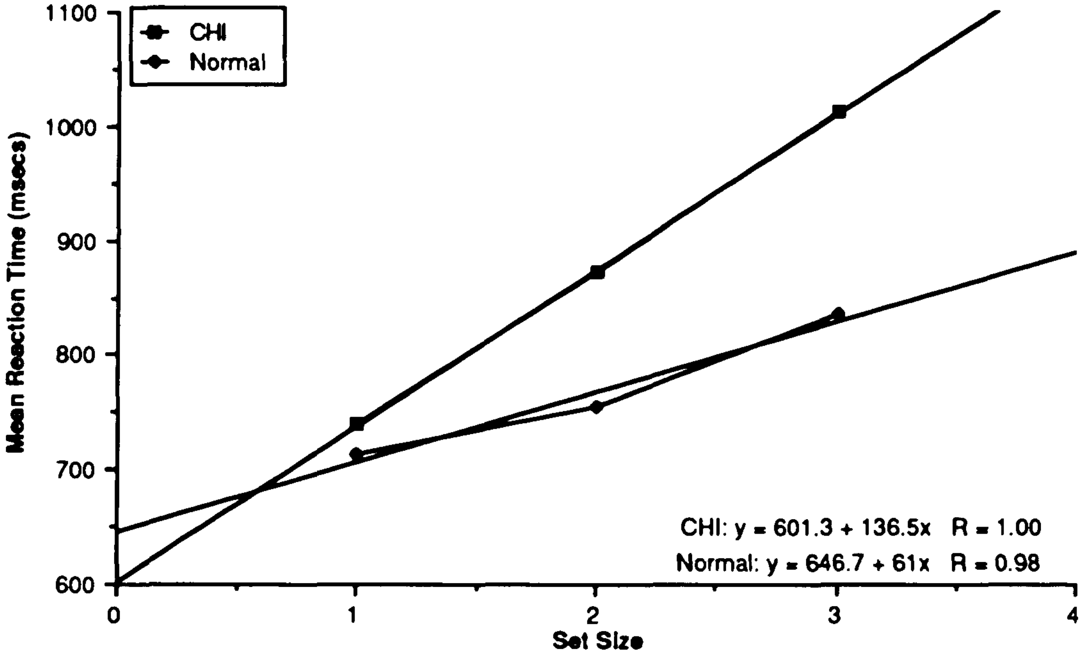


Figure 8. Mean reaction time for correct responses as a function of comparison set size on the Motor Programming task.

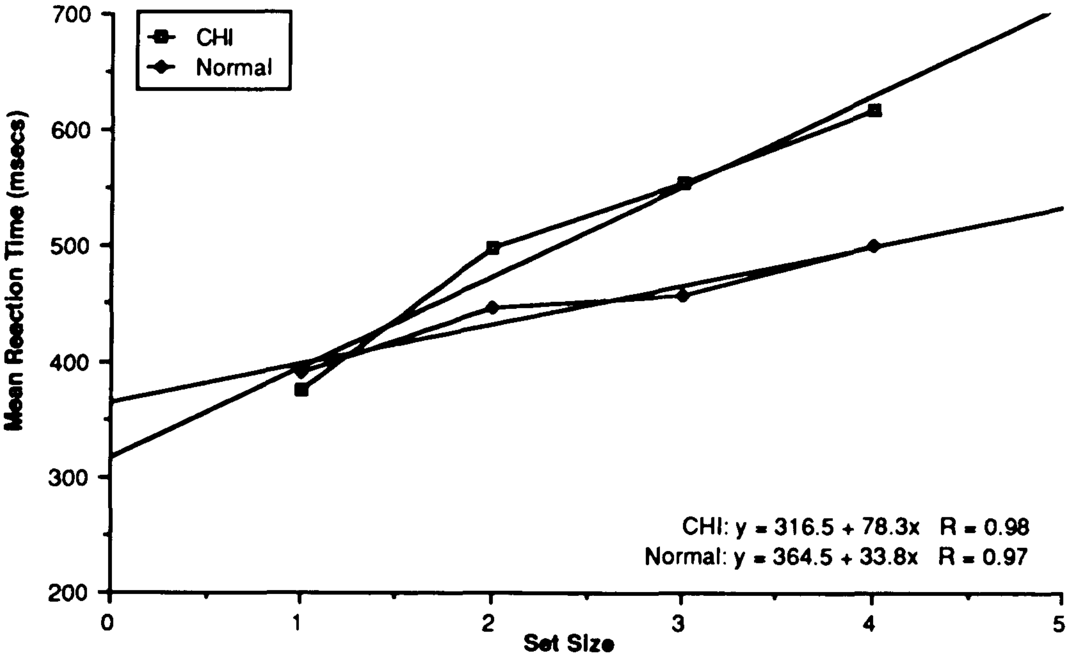
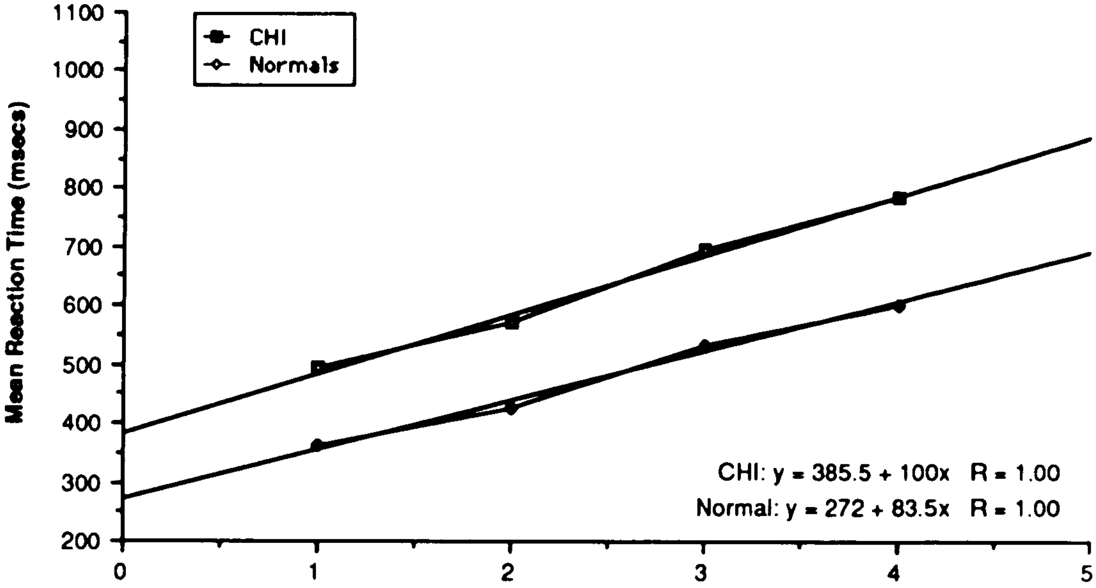


Figure 9. Mean reaction time for correct responses as a function of comparison set size on the Consonant SIM task.

10a. Positive probes



10b. Negative probes

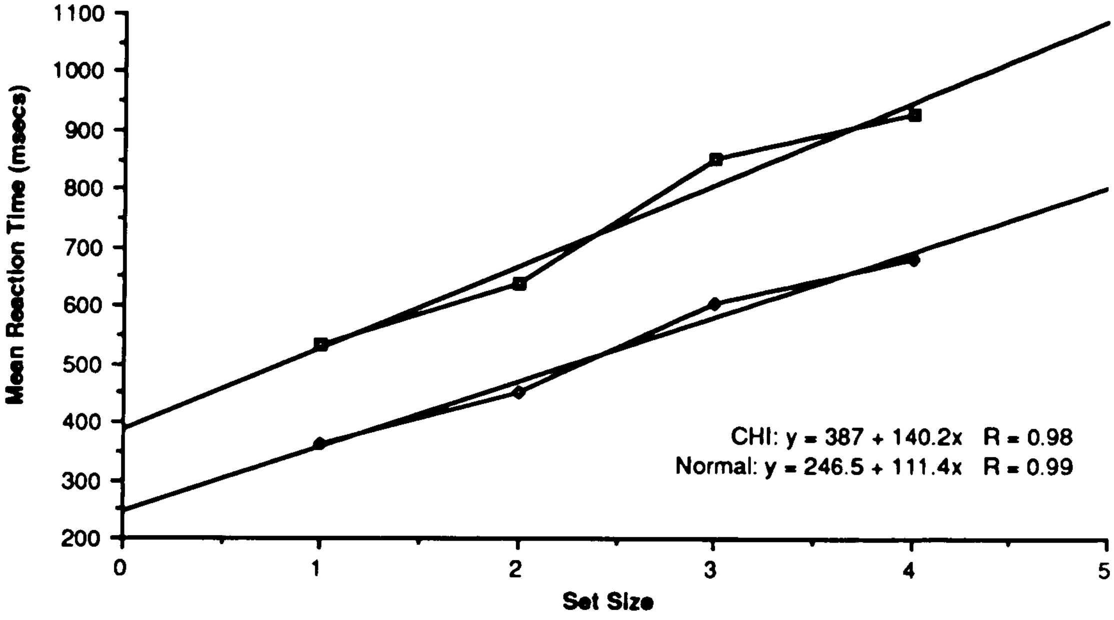


Figure 10. Mean reaction time for correct responses on (a) positive probes and (b) negative probes as a function of comparison set size on the Number SIM task.

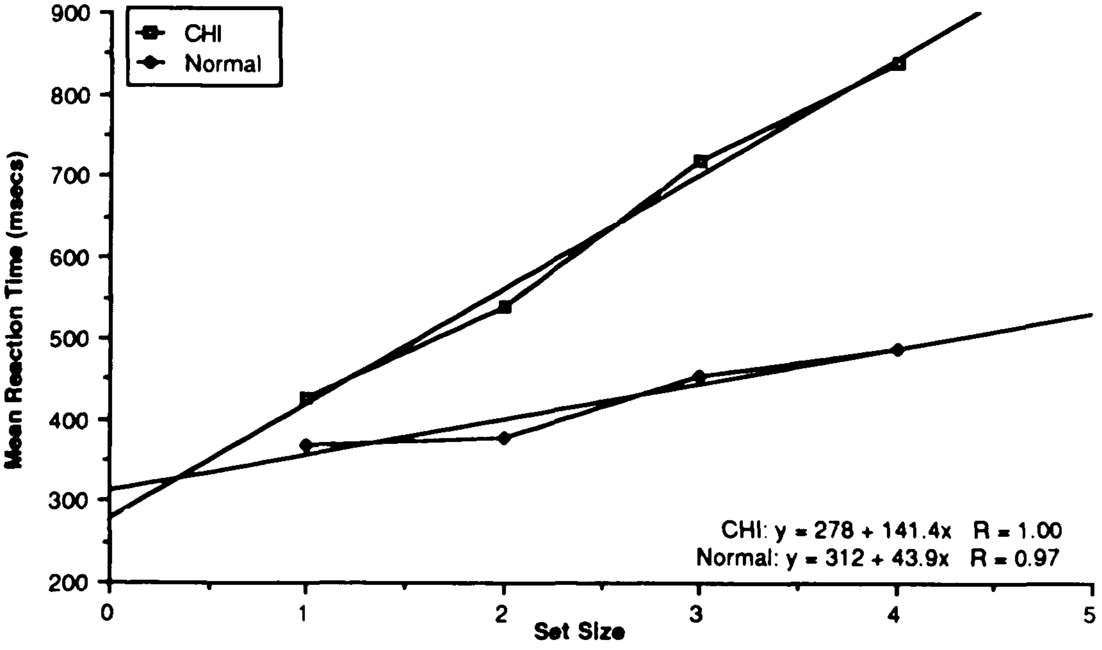


Figure 11. Mean reaction time for correct responses as a function of comparison set size on the Word SIM task.

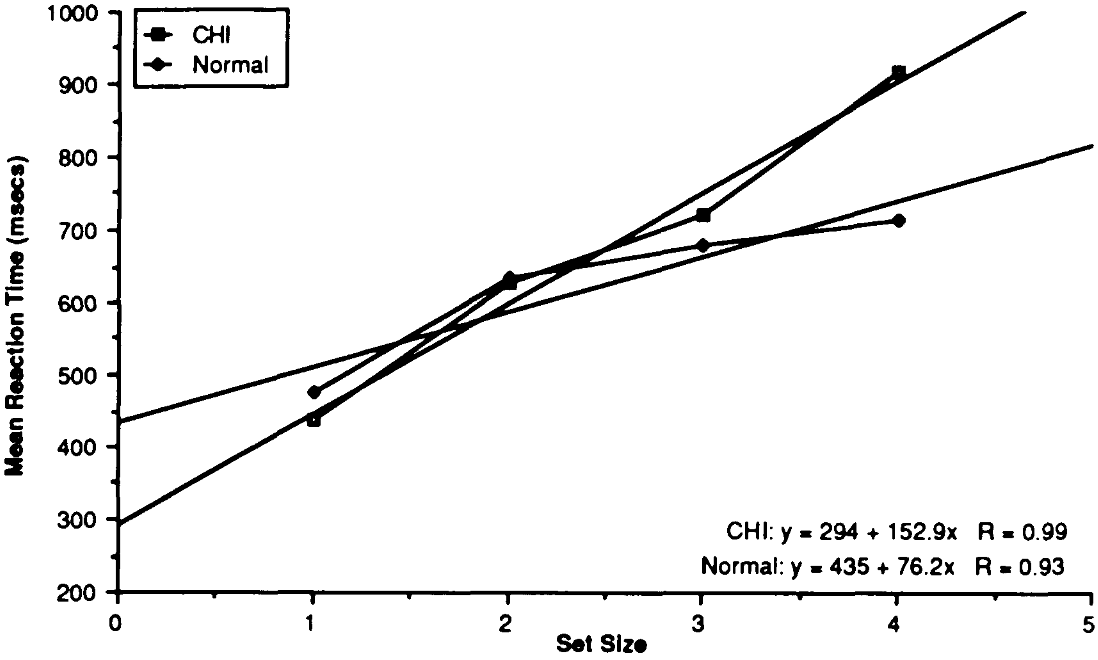


Figure 12. Mean reaction time for correct responses as a function of comparison set size on the Pattern SIM task.

## Comparisons Between SIM Tasks

### Slopes

All main effects were significant: Group (*F*(1,24) =23.90, p<.001); Probe (*F*(1,24) =5.51, p=.027); and Task (*F*(3,72) =7.76, p<.001) with slope estimates greater for CHI than normal subjects, and for negative than positive probe trials, and differing between the four tasks. A significant two-way interaction for Task x Group (*F*(3,72) =6.44, p=.001) showed that, while both groups showed the least changes in slope on the consonant task (Normal: 34 and CHI: 78 msecs/item), they differed in the degree to which the other three tasks produced slope increases. For the normal subjects, rates of comparison processes were slowest for Number (97 msecs/item), faster for Pattern (76 msecs/item), and fastest for the Word (44 msecs/item) task. CHI subjects produced the slowest rates on the Pattern task (152.5 msecs/item), faster for Word (141.5 msecs/item), and fastest for Number (111 msecs/item). The significant Task x Probe x Group interaction (*F*(3,72) =5.52, p=.002) indicated that these between-group differences across the four tasks also differed with respect to positive and negative probe trials, with no clear trend evident.

### Intercepts

There was a significant main effect for Probe (*F*(1,24)=11.307, p=0.003) with intercept estimates on all tasks greater for negative (342 msecs) than positive probe trials (323 msecs). A significant Task x Group interaction (*F*(3,24)=10.33, p<.001) indicated that normal and CHI subjects differed in their intercepts across the four tasks. The time taken to perform the peripheral processes encompassed by the intercept in normal subjects increased in magnitude from Number (260 msecs) and Word (312 msecs) to Consonant (365 msecs) and Pattern (436 msecs), while that of CHI subjects increased from Word (278 msecs) and Pattern (294 msecs) to Consonant (316 msecs) and Number (402 msecs).

### Delayed Identity-Match Tasks (Figs. 13 and 14)

#### Slopes

Mean slope estimates for CHI subjects were significantly greater than those for normals on both Consonant (F(1,24) =25.92, p<.001)(see Figure 13) and Pattern tasks (F(1,24) =14.85, p=.001)(see Figure 14), indicating that the rate at which central comparison processes are made in memory is slower for CHI than normal subjects. A significant Probe by Group interaction (F(1,24) = 6.32, p=.019) was found for the Consonant task, with a greater separation of the groups for negative (CHI: 83.79 msec/item vs. Normal: 30.31 msec/item) than for positive (CHI: 69.93 msec/item vs. Normal: 35.94 msec/item) probe trials.

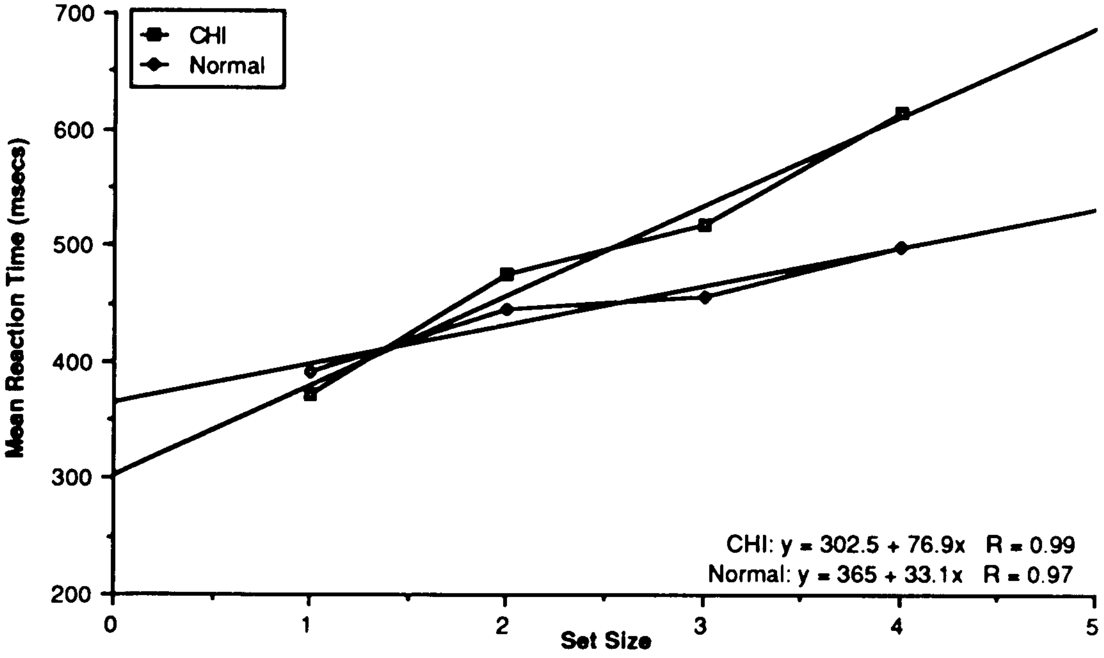


Figure 13. Mean reaction time for correct responses as a function of comparison set size on the Consonant DIM task.

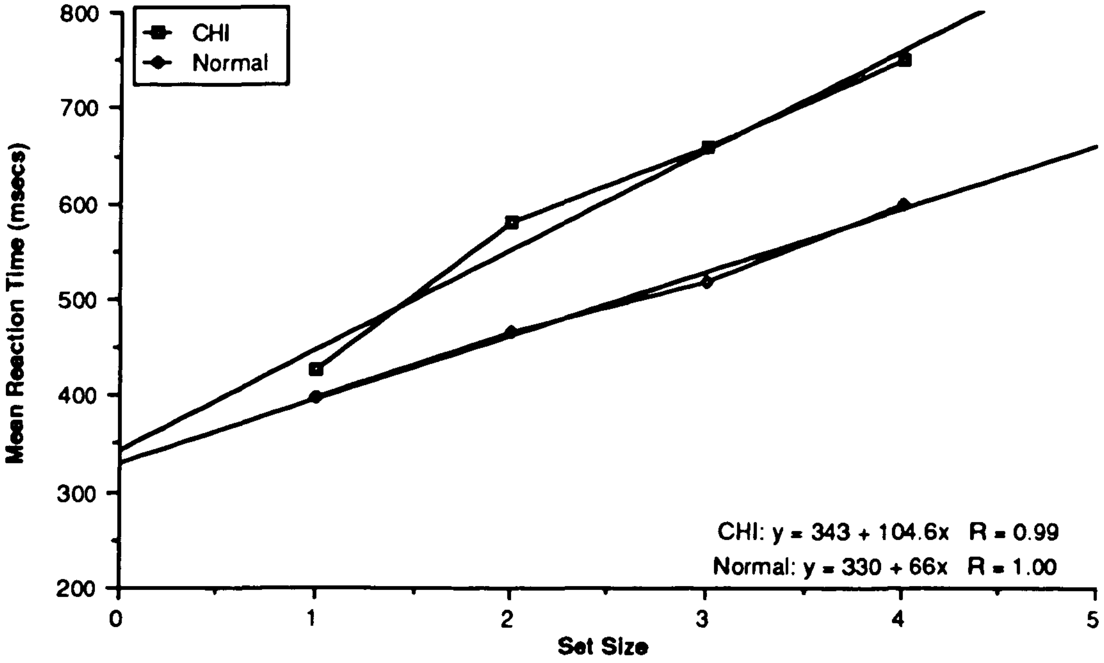


Figure 14. Mean reaction time as a function of comparison set size on the Pattern DIM task.

### Intercepts

A significant between-group difference was found on the Consonant task (*F*(1,24) =4.84, p=.038), indicating that CHI subjects (303.15 msecs) took less time than normals (364.64 msecs) to execute the peripheral sensory-perceptual and motor processes in this task. A significant Group by Probe interaction (*F*(1,24) =4.33, p=.048) was also found, reflecting a greater difference between correct 'Yes' and 'No' responses for normals (40 msecs) than CHI subjects (9 msecs). No significant between-group intercept differences were found on the Pattern task.

## Comparisons Between DIM Tasks

### Slopes

A comparison of the two delayed identity-match tasks showed a significant main effect only for Group (*F*(1,24) =36.69, p<.001), reflecting the slower rate of information processing in the CHI group compared to normals. The absence of other significant main effects or interactions suggests that performance on the two tasks was similar between each group.

### Intercepts

A significant Task (*F*(1,24)=4.901, p=0.037) main effect and Task x Group (*F*(1,24)=5.257, p=0.031) interaction demonstrated that, while the intercept estimates were greater for patterns than consonants, the Consonant task produced a greater difference between the groups in the time taken to execute peripheral processes (Consonant: 364 (normal) vs. 303 (CHI) msecs; Pattern: 329 (normal) vs. 343 (CHI) msecs).

## Comparisons Between DIM and SIM Tasks

### Slopes

For the two Consonant tasks a significant main effect for Group ($\underline{F}(1,24)=29.519$, $p<.001$) confirmed that CHI subjects had greater slope estimates and, therefore, slower rates of processing than normals. The only other significant effect was the Task x Probe x Group ($\underline{F}(1,24)=10.367$, $p=0.004$) interaction. On the Consonant SIM task both CHI and normal subjects produced greater slope estimates for positive than negative probe trials. This pattern was also found in the performance of normals on the delayed consonant task, but was reversed for CHI subjects. This means that the rates of central comparison processes for the CHI group are slower for "No" than "Yes" responses when the probe is compared with the comparison set in memory, but slower for "Yes" than "No" responses when the comparisons are simultaneous.

Comparisons between Pattern SIM and DIM tasks yielded significant main effects for Group ($\underline{F}(1,24)=23.756$, $p<.001$) and Task ($\underline{F}(1,24)=6.255$, $p=.020$) showing slower processing rates for CHI than normal subjects, and for simultaneous (114 msecs/item) than delayed (85 msecs/item) tasks. No significant interactions were found.

### Intercepts

Significant differences were found for Group ($F(1,24)=6.378$, $p<.019$) and Task x Probe x Group ($F(1,24)=8.185$, $p=0.009$). On the Consonant SIM task, normals had negative probe trial intercepts approximately 20 msecs greater than positive probe trials, while CHI subjects showed an even greater separation (76 msecs), meaning that CHI subjects took proportionately longer than normals to make a correct "No" than "Yes" response. On the Consonant DIM task, although normal subjects showed this same trend to a greater degree, with 40 msec difference, the CHI group showed no difference between positive and negative trials.

For the Pattern SIM and DIM tasks significant effects were found for Group ($F(1,24)=5.267$, $p=.031$), Task ($F(1,24)=5.234$, $p=.031$), and Task x Group ($F(1,24)=7.568$, $p=.011$). These findings reflect the greater time taken for CHI subjects to perform sensory-perceptual and motor processes under the delayed matching condition while normals took longer to perform simultaneous identity matches.

## Transformation Tasks (Figs. 15 and 16)

### Slopes

CHI subjects had significantly greater ($F(1,24)=42.47$, $p<.001$) slope estimates, and slower processing rates, on the Categorization task than normals (CHI: 422.33 vs. Normal: 50.09 msecs/item) (see Figure 15). While no Group main effect was found on the Subtraction task, there was a significant

Group by Probe interaction (*F*(1,24) =16.14, p=.001). The rate at which central comparisons involving subtraction occurred were significantly slower for negative (Fig.16b) (CHI: 269.41 vs. Normal: 165.17 msecs/item) than positive (Fig.16a) (CHI: 140.78 vs. Normal: 124.91 msecs/item) probe trials.

### Intercepts

A significant between-group difference (*F*(1,24) =7.50, p=.011) was found for intercept estimates on the Subtraction task, with CHI subjects (797 msecs) taking longer than normals (328.70 msecs) to perform peripheral sensory-perceptual and motor processes. No between-group main effect was found for the Categorization task, but a significant Probe by Group interaction (*F*(1,24) =6.20, p=.020) reflected the greater between-group differences for positive (CHI: 86 msecs vs. Normal: 496 msecs) than negative probe trials (CHI: 506 msecs vs. Normal: 640 msecs).

## Comparisons between Transformation Tasks

### Slopes

Significant differences between the Subtraction and Categorization tasks were found for the Group (*F*(1,24) =47.61, p<.001), and Task main effects (*F*(1,24) =19.63, p<.001) indicating that the rates of information processing were slower for CHI than normals, and for Categorization than Subtraction. The Group by Task interaction (*F*(1,24) =17.04, p<.001) reflected a greater between-group difference in slope estimates indicating that the Categorization (372.2 msecs/item) task slowed processing rates to a greater degree than the Subtraction task (60.6 msecs/item).

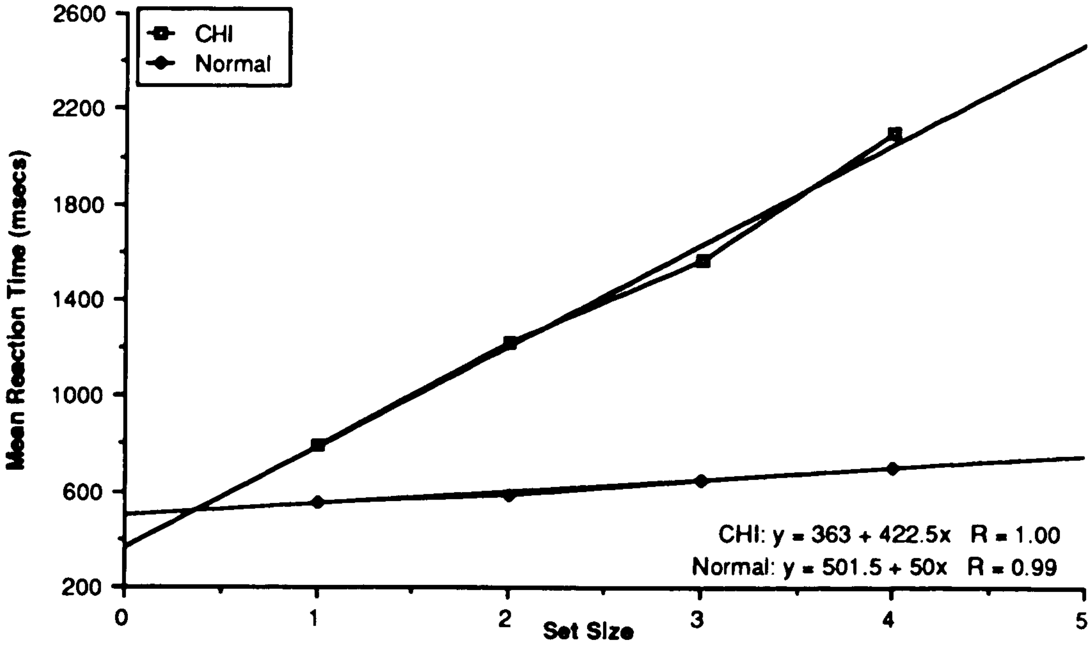
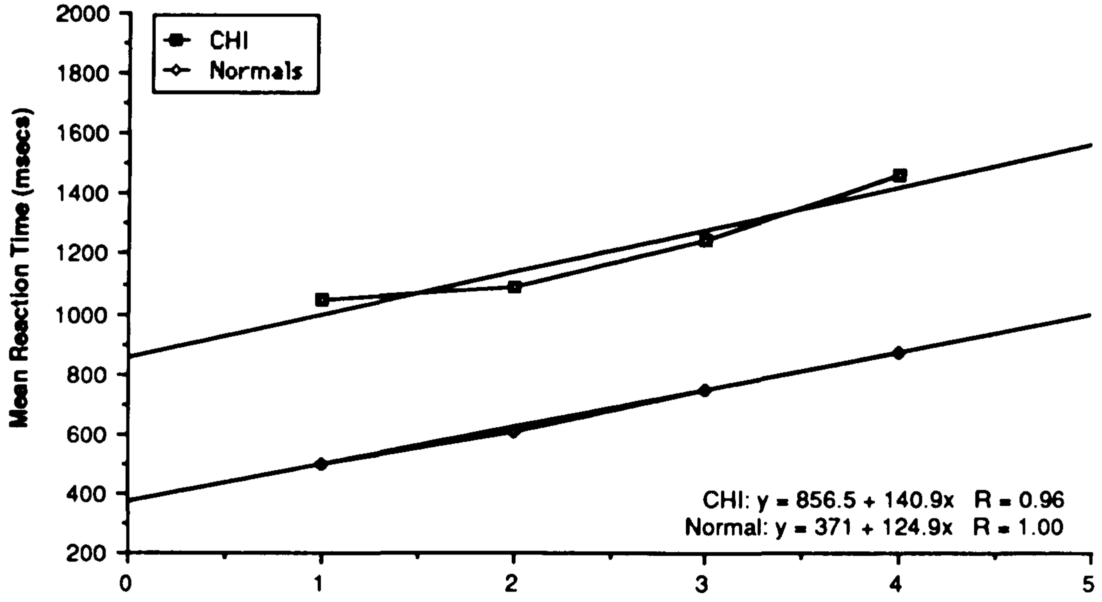


Figure 15. Mean reaction time for correct responses as a function of comparison set size on the Categorization task.

16a. Positive probes



16b. Negative probes

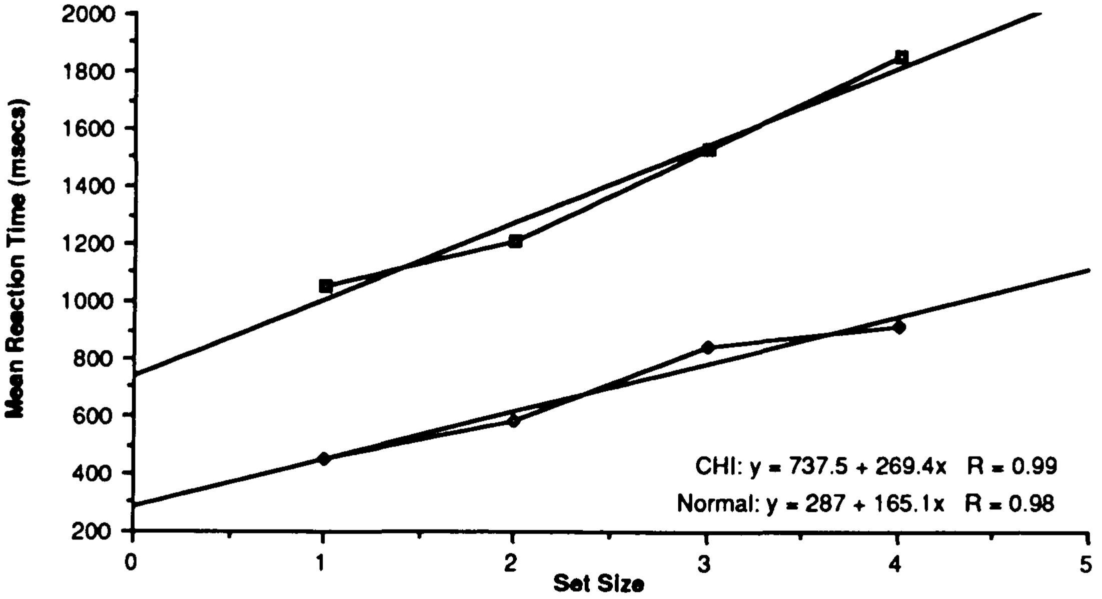


Figure 16. Mean reaction time for correct responses on (a) positive probes and (b) negative probes as a function of comparison set size on the Subtraction task.

### Intercepts

Significantly greater intercepts (F(1,24)=11.822, p=0.002) were found on the Subtraction task (563 msecs) compared to the Categorization task (432 msecs), and trials for negative probes (543 msecs) were greater (F(1,24)=6.136, p=0.021) than positive probes (452 msecs). Significant Task x Group (F(1,24)=10.036, p=0.004) and Task x Probe x Group (F(1,24)=6.604, p=0.017) interactions indicated that the between-group differences in the time taken to execute sensory-perceptual and motor processes were not only greater for "Yes" than "No" responses but also greater for the Subtraction than Categorization task.

## Comparisons Between Transformation and SIM Tasks

### Slopes

For the two number tasks, slope estimates were significantly greater for Subtraction than Number SIM (F(1,24)=4.882, p=.037), and for negative than positive probe trials (F(1,24)=52.122, p<.001). The significant Task x Probe x Group (F(1,24)=5.600, p=.026) interaction showed that, not only was the rate at which the CHI group performed central comparisons involving subtraction significantly slower than that of normals on negative and not positive trials, but that this difference was greater than when the task involved simultaneous matching of numbers.

Comparing the categorization task and word SIM tasks, significant differences were found for Group (_F_(1,24)=37.107, p<.001), Task (_F_(1,24)=69.670, p<.001), and Task x Group (_F_(1,24)=42.586, p<.001) showing the large difference in the CHI group between the rates at which central comparisons involving categorization (422.3 msecs/item) and simultaneous matching of words (141.6 msecs/item) occurred, in contrast to the small difference for the normal group (50.1 vs. 43.95 msecs/item).

### Intercepts

Analysis of intercept estimates for Subtraction and Number SIM revealed only significant main effects for Group (_F_(1,24)=11.404, p=.002) and Task (_F_(1,24)=7.441, p=.012) reflecting the overall greater time to execute sensory-perceptual and motor processes during the Subtraction task compared to Number SIM, and for CHI subjects compared to normals.

On the word tasks, Categorization and Word SIM, significant differences were found for Probe (_F_(1,24)=12.315, p=.002), Probe x Group (_F_(1,24)=6.787, p=.016), and Task x Probe x Group (_F_(1,24)=5.557, p=.027). The absence of any significant differences between the CHI and normal group in the time taken to perform sensory-perceptual and motor processes on the Word SIM task, is contrasted here with performance on the Categorization task where the two groups differed dramatically (CHI: 86 msecs vs normal: 496 msecs) in the time to execute these peripheral processes when correctly identifying a probe word as an exemplar of a member of the comparison set.

## Summary of Slope and Intercept Estimate Analyses

### Slopes

CHI subjects showed significantly greater slope estimates than controls for all tasks, reflecting a slowing in the rate at which central comparison processes were made. For seven of the nine tasks these differences were for responses on both positive and negative trials. For the Number SIM and Subtraction tasks the difference was significant only for slope estimates of negative probe trials.

### Intercepts

No differences in intercept estimates were found on five of the nine tasks: Motor Programming, Consonant SIM, Word SIM, Pattern DIM, and Categorization. This indicates that the two groups did not differ in the time taken to execute the peripheral sensory-perceptual and motor processes involved in these tasks. On two of the nine tasks, Pattern SIM and Consonant DIM, the between-group differences reached significance but these intercepts were smaller for the CHI subjects than normals. On the remaining two tasks, Number SIM and Subtraction, the CHI group produced significantly greater intercepts, and so longer peripheral processing times, than their normal counterparts.

# DISCUSSION

While slowing of reaction timing is a common finding following closed head injury, the partitioning of RT performances into slope and intercept components permits further evaluation of the differential effect of acute mild head injury upon the processing stages associated with these estimates. Sternberg (1969a) has identified at least four distinct processing stages (stimulus encoding, serial comparison, binary decision, and translation/response organization) in the performance of his item recognition task, upon which the nine tasks in this study are based. Slope estimates measure those aspects of each task which change from trial to trial, and reflect the rate at which the central comparison process is performed. Intercept estimates reflect the time taken to perform the more peripheral (with respect to the comparison stage) processes of each task which are relatively constant or stable across trials, such as stimulus encoding, decision-making, and response execution.

The acute mild CHI patients in this study were found to have significantly steeper slopes than normal subjects on all tasks, reflecting a slowing in the rate at which they process information within a number of different cognitive systems. This reduction in processing rate, therefore, is not specific to one system, but reflects a global slowing of behavior. The fact that the slope increases were not accompanied by significant increases in intercept values on seven of the nine tasks suggests that the slowing cannot be attributed to changes in the sensory-perceptual, decision-making, or response execution stages. While the findings of this study can neither confirm nor deny the existence of Sternberg's processing stages, whatever processes underly the slope and intercept intercepts are differentially influenced by acute mild closed head injury. However, support for both the existence of these stages and the sparing of peripheral processes following mild CHI comes from the work of Shum, McFarland, & Humphreys (1990), in which processing stages, encompassed by the intercept estimates in the present study (feature extraction, identification, response selection, and motor adjustment), were shown to be unaffected by mild head trauma.

Intercept differences between the two groups were found on four of the nine tasks. For the Consonant SIM and Pattern SIM tasks, intercept estimates were significantly faster for CHI than normal subjects, but in the Number SIM and Subtraction tasks, intercepts were slower for CHI patients than normals. The significance of slower than normal intercept values on the two number tasks in the CHI group will be discussed later. The finding of CHI intercept estimates which are faster than those of controls may be a product of the interdependence of slope and intercept estimates. If slope estimates have been, for some reason, overestimated for a particular group then, by the fact that the intercept measure is derived from the interpolation of the slope to the y-intercept, it follows that the intercept estimate would be underestimated. This would suggest that, in the case of smaller intercepts in the CHI group, the slope estimates have been overestimated. The use of a larger number of trials on each task or an increase in the number of positive probe sets would increase the stability of the slope estimates in terms of both decreased variability and greater variance accounted for, and would decrease the probability of either under- or over-estimating the slope of the RT function. Consideration of this point in any future research is strongly recommended.

On the Word SIM task, mild CHI subjects had slope estimates more than three times those of normals, while on the Categorization task, CHI subject performance was approximately eight times slower than that of their normal counterparts. The Categorization task seems to have been particularly difficult for the CHI subjects as, on average, they required 280 msecs more per item to categorize a word than to perform an identity match. In contrast, normal subjects required only an average of 6 more msecs per item to categorize than to match a word. As there were no intercept differences between the two groups on these tasks, the stages that are vulnerable to mild head trauma must include those encompassed by the categorization process.

CHI subjects were more than twice as slow as control subjects in their rate of processing consonants. Neither group, however, showed a difference in their performance between Consonant SIM and DIM tasks. This may be because both CHI and normal subjects performed the equivalent of delayed identity-matches during simultaneous identity-match tasks. During delayed tasks, subjects are required to make comparisons between the probe and a representation of the comparison set in memory. This process is not necessary for simultaneous tasks, as the comparison set remains on the screen, but subjects may memorize the comparison sets and, in effect, perform a delayed identity-match. This may be a more efficient strategy than repeatedly scanning the set area for stimuli which are already represented in memory. An alternative explanation for the lack of a difference in performance of SIM and DIM tasks is that the time taken to scan the on-screen comparison set items in the SIM tasks does not differ significantly from the time needed to scan their representation in memory in the equivalent DIM task. In either case, the strategy used does not appear to be vulnerable to the effects of mild head trauma.

On the two number tasks, Number SIM and Subtraction, the presence of a significant difference for negative, but not positive, slopes, and the significantly longer intercept estimates was most likely a consequence of differences in comparison set procedures. The frequent changing of comparison sets may have slowed response times by increasing subject uncertainty as to the accuracy of an identity match. In effect, subjects faced the task of not only scanning a newly displayed comparison set, but also inhibiting affirmative responses to probes that resembled a member of a previous comparison set. In previous research (Senior & Tweedy, 1984,1986), numbers were used as comparison sets during practice trials for a consonant memory-scanning task identical to the delayed consonant identity-match task used in this study. Although only sets of two and four numbers were used, the findings in the earlier studies were similar to those for comparable set sizes of consonants for both head-injured and normal subjects in the present study. As the performance of both CHI and normal subjects on the Consonant SIM task fully replicate the findings of the earlier study, it is reasonable to assume that had this procedure been used for the number task, similar results would have been found. This is further supported by the work of Sternberg (1975), who has consistently demonstrated similar findings in normal subjects with memory-scanning tasks using consonants and numbers as probe stimuli.

Brouwer (1985) tested head-injured patients within a few weeks of the resolution of post-traumatic amnesia, using a simple arithmetic test. Subjects memorized sets of one, two, or three digits, and were then presented with addition problems (e.g. 3 + 2 = ?). Subjects pressed a 'yes' button if the solution to the problem matched a member of the memory set, and a 'no' button if it did not. Brouwer found that the increase in RT with increasing memory set size was greater for the head-injured than normal subjects, and was significantly greater for 'no' than 'yes' responses. Although the task used differed in many ways from the arithmetic task used in the current study, the results suggest that the difference for negative probe slopes found for the subtraction task was due to the minor head injury and not procedural factors.

The presence of greater than normal slopes in the CHI group on the Motor Programming task, indicating a slowed rate of motor programming, was unexpected, as deficits in this system have not previously been found in this clinical population. The actual time taken to execute the motor responses was not slowed, as indicated by normal intercept estimates, but CHI patients took longer to prepare or program these acts. This means that while mild CHI patients do not take longer to physically execute a motor act they take longer to organize and prepare it. This would suggest that the more complex the motor sequence required, the longer mild head-injured patients will take to perform the task, compared to normals. This difficulty may have been overlooked in previous studies, as there is a tendency to simplify response requirements in assessing clinical populations, and also because patients with mild head injury present with normal neurological findings. The finding has implications for mild head-injured patients and their ability to efficiently perform complex motor behaviors that require rapid preparation and coordination, such as driving a car.

### Hypothesized Basis of the Slowed Rate of Information Processing

Salthouse (1984) has used a computer analogy to explain slowed rate of information processing with respect to aging. Some of these hypotheses will be discussed with reference to the present study.

### Limitations in input/output rate

Slower rates of information transmission in head-injured subjects could be attributed to slower speeds of peripheral communication, either because of sensory or motor delays. If this were so, however, then time differences between normal and head-injured subjects should remain constant with increases in task complexity as long as the input and output processes remained the same. This is clearly not the case with respect to the current study. The slope differences between CHI patients and controls generally increase as task complexity increases from simultaneous through delayed to transformation identity-matches. Alternatively, no differences should be observed in the rate of internal processes when they are measured independently of the duration of input and output stages. Differences in speed of processing between head-injured and normal subjects should be eliminated by bypassing the input and/or output phases of processing. If, for example the rate limiting factor were to be the execution of the motor response, then differences should disappear if measurements were made prior to this response. This is effectively evaluated through the partitioning of RT into slopes and intercepts, as the intercept estimate includes all input/output processes. The lack of intercept differences between mild CHI and normal subjects in the present study suggests that peripheral slowing cannot account for the differences in speed of behavior.

### "Software" differences

Another explanation is that qualitatively different programs, or sequences of control, form the basis for differences in processing speed between normal and CHI subjects. If the system used is less efficient than another system, it will produce longer delays for the same activities even though the two systems may be physically identical. For example, it could be hypothesized that poor preparation is responsible for at least some of the speed of processing differences between CHI and normals, either due to a failure to develop optimal readiness for a specific signal or to a decreased ability to maintain a prepared state. Alternatively, it could be the case that stimulus information is used inefficiently or that speed is sacrificed in a trade-off for more accurate performance. Hypotheses such as these would predict that there should be no differences in speed of performance between CHI and normals when the task minimizes or eliminates the possibility of variations in strategy or control processes. Furthermore, differences should increase in magnitude with increases in task complexity because of the greater opportunity for the employment of differential strategies. Additionally, differences in speed of processing would be expected to be eliminated with prolonged practice since both head-injured and normal subjects would then have the opportunity to acquire optimal strategies.

While increasing task complexity does seem to produce greater slope differences between the CHI and normal subjects, as with the categorization and word identity-match, significant between-group differences are evident on even the simplest tasks, suggesting that strategy differences do not capture the underlying differences between these two groups.

### Capacity of working memory

Delays in information processing in head-injured subjects may be due to a diminished working memory space. If this hypothesis is correct, there should be little or no difference between CHI and normals for simple tasks that can be performed within the limits of a small working memory, with differences emerging as task complexity increases and the limitations of a small working memory system are exceeded. By using comparison sets no greater than four in size, all tasks in the current study used stimulus sets within the working memory capacity of all subjects. For example, all subjects in the present study were required to show that they had memorized the comparison sets in the Consonant DIM task by recalling them forwards and backwards. Although the reported increases in response time with increasing comparison set size could be viewed themselves as resulting from a diminished working memory space, no significant differences in error rates were found between the two groups at any set size. If a decrease in working memory capacity was responsible for the slowed rate of information processing in the CHI group then this should have been accompanied by a disproportionate increase in the error rate for this group, much in the same way that errors increase in normals when working memory capacity is exceeded. Nor can increased response time as a function of increased set size be viewed as being specific to head injury as this also occurred within the normal group.

### Concurrent processing demands

Another possibility is that processing time will be greater in systems that either must allocate their resources to a greater number of jobs, or must allocate a smaller period of time to each job. Reduced efficiency in the allocation of resources may be due to changes in level of arousal or differences in motivational states. If this were the case, then reductions in processing speed should be eliminated if conditions were so arranged that subjects would clearly benefit if they devoted all of their resources to the performance of the experimental task. While this hypothesis cannot be directly evaluated on the basis of the current study, the fact that CHI subjects seemed to adopt a delayed identity-match strategy in performing the Consonant SIM task suggests that mild head-injured subjects have sufficient resources that they can allocate a memory scanning process to a task that requires only a simultaneous identity-match.

### "Hardware" Differences

Differences in the speed of processing might be attributed to structural changes that alter the "clock speed" or cycle time per operation. In such a case, two systems with different cycle times would differ in their processing times even if the same operations were performed in exactly the same manner. All processes under the control of the central processing unit would take longer in the system with the slower clock speed. Furthermore, the magnitude of speed differences should increase with increases in processing complexity of the task to be performed.

This hypothesis would suggest that head-injured individuals, with slow cycle times, should be slower across a variety of measures compared with normal individuals. The findings of the current study support this hypothesis. While both groups demonstrated increases in processing times with increasing task complexity, mild head-injured subjects showed slower rates of information processing compared to normals. Moreover, mild head injury appeared to specifically affect central processing stages as evidenced by slope increases and spare sensory-perceptual, decision-making, and response-execution processes encompassed by the intercept, which are presumably under the control of different systems. In continuing the computer analogy, this would be akin to reducing the clock speed of the central processing unit of a computer while leaving software, and disk drives, keyboard, and other hardware unchanged.

The most likely locus for a central clock mechanism vulnerable to this type of injury is in the brainstem. Folz & Schmidt (1956) and Ward (1966) viewed the reticular core as the site of dysfunction in concussion, and Oppenheimer (1968) demonstrated microglial clusters in the brainstems of patients who had sustained mild head injuries. The alterations of consciousness resulting from mild head injury indicate that shearing forces during the trauma are of sufficient magnitude to, at least temporarily, disrupt brainstem alerting functions (Ommaya & Gennarelli, 1974). Povlishock et al. (1983) have demonstrated the vulnerability of the long axon tracts coursing through the brainstem, and these findings have been confirmed by other investigators (Bakay, et al., 1977; Brown, Yoshida, Canty, & Verity, 1972; Jane et al., 1985). How this brainstem axonal damage might produce a general slowing in the rate of information processing in mild head-injured patients is unclear. However, Luria (1966) proposed that the reticular formation plays an essential role in the regulation of arousal and active states and, given the extensive interconnections the reticular system has with the frontal lobes and other cortical and subcortical structures, it appears that this system may play an important role in virtually all functions of the nervous system (Brodal, 1969).

## Conclusions

The presence of a general deficit in the rate of information processing following mild closed head injury seems clear, and may explain the particular pattern of neuropsychological deficits found in such patients. Those standardized tests which seem most useful for evaluating mild head trauma, such as memory, attention, and verbal fluency tasks, share temporal constraints in the form of either time limits or paced presentation of stimuli. Below normal performance may not reflect dysfunction in those cognitive systems commonly associated with these tests, but rather may be due to an inability to process the task requirements within the normally allotted time.

The tasks utilized in this study, evaluated the relative impact of brain injury upon different processing stages and allowed the analysis of correct responses rather than the deficits which form the basis of much clinical assessment. Performance on these tasks can be viewed with confidence as deficits measured on one component occur within the context of normal performances on the other.

The apparent specificity of the effect on the slope estimate in mild head injury, with simultaneous sparing of the intercept component, may permit effective determination of the level of severity of head trauma, as moderate and severe injuries additionally influence those processes subsumed under the intercept estimate. Psychogenic etiologies can potentially be discriminated from organic etiologies, as disorders associated with these varied origins produce differential slope and intercept effects. Disorders currently described as functional or psychogenic tend to impact upon intercept estimates and spare slope measures (paranoid and non-paranoid schizophrenics: Highgate-Maynard & Neufeld, 1986; cultural-familially retarded children: Silverman, 1974; depression: Koh & Wolpert, 1983), while organic disorders (other than mild head injury) almost universally produce slope and intercept increases (Parkinson's disease: Wilson, et al., 1980; aphasia: Warren, Hubbard, & Knox, 1977; alcoholism: Mohs, et al., 1979; Korsakoff patients: Naus, Laird, Cermak, & De Luca, 1977; Friedrich's ataxia: Hart, et al., 1985; multiple sclerosis: Rao, St. Aubin-Faubert, & Leo, 1989; and HIV infection: Hart, et al., 1990).

Within the area of cognitive rehabilitation, the focus is often placed on those cognitive systems that, through neuropsychological evaluation, have been identified as dysfunctional. For example, poor performance on a memory task may lead to remediation exercises that emphasize list-learning and memory games. Improvement in test scores on subsequent evaluations may be the result of this focus, in effect training the patient to perform better on the very tasks used to monitor recovery. Clearly, tasks are needed that can effectively track recovery of functions that are not directly related to the extant intervention strategies. The Paced Auditory Serial Addition Test has been useful in the monitoring of cognitive rehabilitation of patients with mild head injury (Gronwall, 1986), and RT tasks such as those used in the present study may prove even more sensitive to the subtle cognitive changes in this population.

Of the nine tasks used in the present study, the Consonant DIM and Motor Programming tasks seem the most promising in this regard. Over the last twenty years a large body of data has been amassed concerning the performance of both normals and a wide variety of patient populations on the Consonant DIM or memory scanning paradigm. The task requirements are readily understood by most patients and accommodations, such as using voice-key activation, can be made for those patients unable to use response keys. The Motor Programming task, while easily mastered by patients, presents greater restrictions in response requirements. Nonetheless, it focuses on an aspect of behavior that is difficult to evaluate and may prove to be of particular use in the evaluation of movement disorders. While these tasks show great potential with respect to the assessment and treatment of mild head-injured patients, further development and research is necessary to determine their psychometric properties before using them for assessment purposes.

## Appendix A. Instructions to Subjects

### Motor Programming

"In this task I am going to ask you to learn a specific pattern of key presses. For this you will be using three keys - **J**, **K**, and **L** and the index, middle, and ring fingers of your right hand. Place your three fingers on the keys like this [demonstrate-placing the index finger on the J key, middle finger on K, and ring finger on L]. Now you place your fingers there. [The practice screen is displayed]. See this large central box? [indicate]. When a star appears in the middle of this box I would like you to press the keys as quickly as you can in a particular order. For this part, when you see the star I want you to press the left key [indicate], then the right key [indicate], and then the center key [indicate. Repeat the movement three times]. Now you practice it. It is important that you press the keys in this order only when the star appears. Do you have any questions? [Answer any questions]. You can now practice the key press orders. If you press the keys in the wrong order, the computer will let you know by beeping. [Ten practice trials are performed] Are you ready to continue? Good! Remember only respond when the star appears!

[Test trials begin. Portions of the above instructions are repeated to demonstrate, practice, and test the two key-press (J-L) and one key-press (J) sequences].

For the rest of the tasks you will be shown some numbers, pictures, words, and letters and will be asked to make **Yes** or **No** decisions about them. In each case what you are comparing these number, pictures, words, or letters to will be different, but all decisions involve either a Yes or No response. This key [examiner indicates the **N** key] is the 'YES' key. If your answer is Yes you will press this key as fast as you can. This key [examiner indicates the **M** key] is the 'NO' key. If your answer is No you will press this key as quickly as you can.

### Simultaneous Identity Match Tasks

In this task I want to see how quickly you can match Letters/Pictures/ Numbers/Words on the screen. See these Letters/Pictures/Numbers/Words [indicate the stimuli displayed in the comparison box in the upper third of the screen]. Letters/Pictures/Numbers/Words will appear here one at a time [indicate the box in the center of the screen] Your task is to indicate whether or not this Letter/Picture/Number/Word is the same as one of the Letters/Pictures/ Numbers/Words up here [indicate comparison box]. If the Letter/Picture/Number/ Word is the same as one of these [indicate stimuli in comparison box] press the Yes key. If it is not the same, press the No key. When you press a key the Letter/Picture/Number/Word will disappear and shortly another will appear for you to respond to.

[Sample stimulus appears in probe box]

For example, this [indicate probe stimulus] is the same as this [indicate equivalent stimulus in comparison box] so you would press the 'YES' key [stimulus disappears and is replaced with an unmatched probe] Now this Letter/Picture/Number/Word is not the same as any of these [indicate comparison stimuli] so you would press the "NO" key.

---

Number Simultaneous Identity Match Instruction Only: [After the second sample trial the numbers in the comparison box are replaced by a new set of numbers that flash for two seconds and then remain on screen] See how the numbers that were here [indicate comparison box] have changed to a new set of numbers. This will happen sometimes during this task. The numbers flash for a little while so that you will notice that they have changed. Your task is still the same except that you have to decide whether the number here [indicate the probe box] is the same as any one of these new numbers [indicate the comparison box]

---

Remember to work as quickly as you can and try not to make any mistakes. If you do make a mistake, don't stop, just keep on going. Do you have any questions? [explain/clarify as necessary]

[Practice trials commence. On subsequent blocks indicate the change in size of the comparison set with "Now there are [number] Letters/Pictures/ Numbers/Words here" and then continue with the trials].

### Consonant Delayed Identity Match

In this task I want to see how quickly you can identify letters you have learned. I would like you to learn the letters inside this box - **I O**. [Indicate the letters displayed on the the monitor in a box in the upper third of the screen. Recall is tested by requiring the subject to correctly repeat the letters forwards and backwards twice].

[The screen clears]

Now, in this box (indicate the center of the screen), letters will appear one at a time. Your task is to indicate whether or not the letter in the box is the same as one of the letters you have just learned. You do this by pressing the Yes or No key. If the letter on the screen is the same as one you learned press the Yes key. If it is not the same, press the No key. When you press a key the letter will disappear and shortly another letter will appear for you to respond to.

[Sample letter appears]

For example, this is an "I" [point to the letter on the monitor] and since it is one of the letters you learned you would press the 'YES' key [demonstrate this]. Note that this letter is now gone, and a new letter has appeared, an "E". Since, this is not "I" or "O" you would press the "NO" key [demonstrate].

You should work as quickly as you can and try not to make any mistakes. If you do think you have made a mistake, do not stop, just continue working. Do you have any questions? [explain/clarify as necessary]

I would like you to continue with these trials.

[Practice trials commence. On subsequent blocks indicate the memory set and check that it has been learned, then allow the subject to continue with the trials].

### Pattern Delayed Identity Match

In this task I want to see how quickly you can identify pictures you have just seen. When you press this key [indicate the long space bar] a number of pictures, as many as four, will appear here [indicate the comparison box and press space bar to display comparison stimuli]. When you release the space bar these pictures will disappear, so don't release it until you have had a good look at each of them. A little while after you release this key a picture will appear here [indicate the probe box; release space bar; one second later a matched picture appears in the probe box]. If this picture is the same as one of those you have just seen then press the Yes key as quickly as you can, otherwise press the No key. [Demonstrate samples]

Do you have any questions? [explain/clarify as necessary]

I would like you to continue with these trials.

[On subsequent blocks indicate that there will be a different number of pictures displayed in the comparison box]

Subtraction Identity Match

In this task, you have to do some simple subtraction. Numbers will be displayed here [indicate comparison box]. When a number appears here [indicate probe box] you must decide whether or not this number is three less than any of the numbers displayed up here [indicate comparison]. For example, [begin sample trials] the numbers here [indicate comparison] are 23, 85, 37, and 16 and the number here [indicate probe] is 82. 82 is two less than 85 so you would press the Yes key. The next number is 17. You would press No here because 17 is not two less than any of these upper numbers. Sometimes the numbers up here will change and flash for a couple of seconds. The flashing is to warn you that the numbers have changed, but your task is still the same - to decide whether the number here [indicate probe] is three less than any of the numbers displayed up here [indicate comparison].

[Continue with practice trials]

Any questions? [Explain as necessary]

[Begin the first block of test trials. At the beginning of each block point out that the number of digits displayed has changed]

Class Exemplar Categorization Match

In this task, a number of categories, up to four, will appear here [indicate comparison box]. Words will appear one at a time in the center box [indicate]. If this word is a member of any one of the categories displayed up here [indicate], then press the Yes key. If the word is not a member of a category then press the No key. For example, [begin sample trials] here the categories are Occupation, City, and River and the word DOG has been displayed in the center box, you would press the 'NO' key as DOG is not an occupation, city, or river. The next word is DOCTOR. This is an occupation so you would press the Yes key. If you are ready, then continue with these trials.

[When the subject has completed the trials]

Do you have any questions? [Explain as necessary]

[Begin first block of trials. When the categories are displayed, indicate them and then begin the trials] .

## Appendix B. Word Stimuli for 10 Target Categories used in Simultaneous Word Identity and Class Exemplar Categorization Tasks

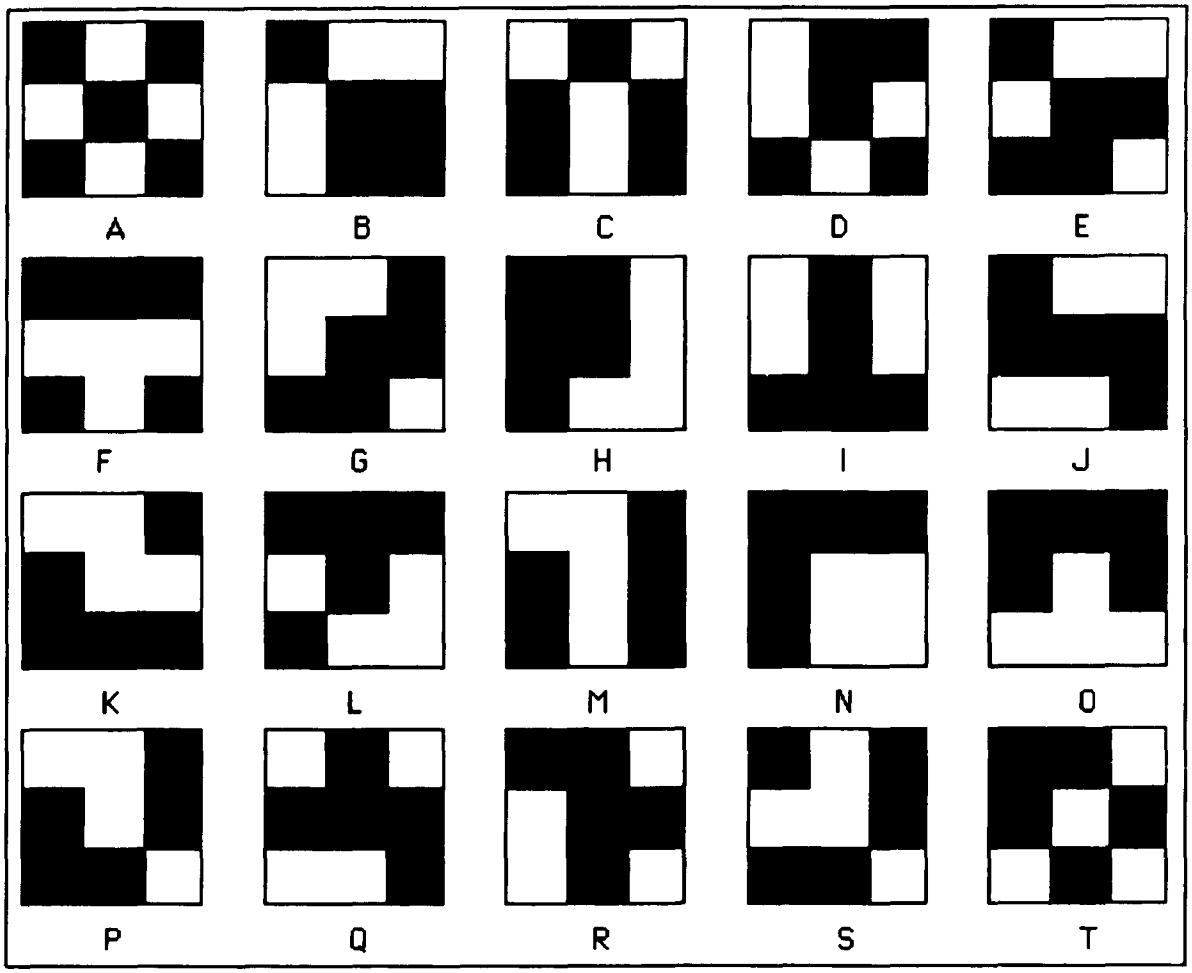
| **Comparison Set:** Set 1 | | Set 2 | |
|---|---|---|---|
| **Category:** Animal | | Insect / Flower | |
| Positive probes | Negative probes | Positive probes | Negative probes |
| leopard (6) | plumber (6) | ladybug (8) | giraffe (12) |
| raccoon (4) | sailing (5) | begonia (5) | grenade (6) |
| monkey (9) | violet (8) | orchid (9) | rattle (5) |
| rabbit (6) | hammer (3) | hornet (3) | dagger (3) |
| horse (26) | steel (31) | daisy (24) | theft (18) |
| tiger (22) | penny (22) | tulip (20) | truck (19) |
| mouse (8) | polio (9) | lilac (6) | stick (5) |
| wolf (4) | rope (4) | flea (6) | cold (7) |
| goat (10) | club (10) | wasp (9) | bomb (10) |
| lion (22) | dime (24) | gnat (16) | corn (18) |
| bear (20) | sofa (19) | rose (45) | chair (47) |
| cat (41) | gun (45) | bee (21) | car (14) |
| Mn: 14.83 | 15.5 | 14.33 | 13.67 |
| SD: 11.42 | 12.99 | 11.93 | 11.91 |
| $t(22) = -1.06$, $p=.314$ | | $t(22) = 0.67$, $p=.507$ | |

Note. Numbers in parentheses refer to relative frequency measures from Howard (1979). No significant differences were found between any of the mean frequency values for positive or negative sets.

| **Comparison Set:** Set 3 | | Set 4 | |
|---|---|---|---|
| **Category:** Fruit / Metal / Sport | | Bird / Cloth / Fish / Tree | |
| Positive probes | Negative probes | Positive probes | Negative probes |
| apricot (7) | zoology (7) | haddock (5) | cabbage (9) |
| bowling (5) | chicken (2) | swallow (5) | bicycle (8) |
| bronze (9) | nephew (13) | velvet (8) | botany (8) |
| skiing (5) | artist (5) | canary (8) | turnip (6) |
| peach (30) | table (46) | maple (29) | knife (44) |
| lemon (11) | train (11) | shark (16) | sword (15) |
| rugby (6) | spear (4) | denim (6) | fraud (5) |
| lime (3) | drum (2) | sole (7) | wife (5) |
| lead (9) | cent (3) | crow (11) | car (11) |
| golf (20) | ball (19) | pine (22) | desk (25) |
| iron (42) | aunt (43) | silk (36) | doll (25) |
| tin (20) | son (16) | oak (29) | pea (26) |
| Mn: 13.92 | 14.25 | 15.17 | 15.58 |
| SD: 11.94 | 15.20 | 11.04 | 12.0 |
| *t*(22) = -0.21, *p*=.839 | | *t*(22) = -0.24, *p*=.815 | |

*Note.* Numbers in parentheses refer to relative frequency measures from Howard(1979). No significant differences were found between any of the mean frequency values for positive or negative sets.

Appendix C. Patterns used in the Pattern Simultaneous and Delayed Identity-Match Tasks.



## Appendix D. Polynomial Tests of Order for the Set Size Variable on the Nine Tasks.

| Polynomial | Source | SS | DF | MS | F | P |
|---|---|---|---|---|---|---|
| Motor Programming | | | | | | |
| Linear | Set Size | 508613.0 | 1 | 508613.0 | 43.04 | <0.001 |
| | Error | 283642.6 | 24 | 11818.4 | | |
| Quadratic | Set Size | 2304.1 | 1 | 2304.1 | 0.43 | 0.520 |
| | Error | 129999.6 | 24 | 5416.6 | | |
| Consonant Simultaneous Identity-Match | | | | | | |
| Linear | Set Size | 148943.4 | 1 | 148943.4 | 25.21 | <0.001 |
| | Error | 140146.9 | 24 | 5839.5 | | |
| Quadratic | Set Size | 1409.6 | 1 | 1409.6 | 0.28 | 0.602 |
| | Error | 121227.7 | 24 | 5051.2 | | |
| Cubic | Set Size | 6950.3 | 1 | 6950.3 | 2.18 | 0.153 |
| | Error | 76564.7 | 24 | 3190.2 | | |
| Pattern Simultaneous Identity-Match | | | | | | |
| Linear | Set Size | 3402530.6 | 1 | 3402530.6 | 124.05 | <0.001 |
| | Error | 658289.3 | 24 | 27428.7 | | |
| Quadratic | Set Size | 45853.2 | 1 | 45853.2 | 9.88 | 0.004 |
| | Error | 111348.6 | 24 | 4639.5 | | |
| Cubic | Set Size | 58136.1 | 1 | 58136.1 | 20.30 | <0.001 |
| | Error | 68785.1 | 24 | 2866.0 | | |
| Number Simultaneous Identity-Match | | | | | | |
| Linear | Set Size | 1235164.5 | 1 | 1235164.5 | 209.66 | <0.001 |
| | Error | 141390.0 | 24 | 5891.3 | | |
| Quadratic | Set Size | 244.3 | 1 | 244.3 | 0.06 | 0.804 |
| | Error | 93522.4 | 24 | 3896.8 | | |
| Cubic | Set Size | 14272.3 | 1 | 14272.3 | 2.19 | 0.152 |
| | Error | 156309.4 | 24 | 6212.9 | | |
| Word Simultaneous Identity-Match | | | | | | |
| Linear | Set Size | 572005.4 | 1 | 572005.4 | 89.21 | <0.001 |
| | Error | 156578.2 | 24 | 6524.1 | | |
| Quadratic | Set Size | 871.8 | 1 | 871.8 | 0.36 | 0.553 |
| | Error | 102377.4 | 24 | 4265.7 | | |
| Cubic | Set Size | 2221.2 | 1 | 2221.2 | 0.51 | 0.481 |
| | Error | 42386.4 | 24 | 1766.1 | | |

| Polynomial | Source | SS | DF | MS | F | P |
|---|---|---|---|---|---|---|
| | | Consonant Delayed Identity-Match | | | | |
| Linear | Set Size | 142647.8 | 1 | 142647.8 | 29.74 | <0.001 |
| | Error | 115112.9 | 24 | 4796.4 | | |
| Quadratic | Set Size | 607.2 | 1 | 607.2 | 0.22 | 0.647 |
| | Error | 67660.9 | 24 | 2819.2 | | |
| Cubic | Set Size | 7658.5 | 1 | 7658.5 | 4.99 | 0.035 |
| | Error | 36843.9 | 24 | 1535.2 | | |
| | | Pattern Delayed Identity-Match | | | | |
| Linear | Set Size | 572005.4 | 1 | 572005.4 | 89.21 | <0.001 |
| | Error | 156578.2 | 24 | 6524.1 | | |
| Quadratic | Set Size | 871.8 | 1 | 871.8 | 0.36 | 0.553 |
| | Error | 102377.4 | 24 | 4265.7 | | |
| Cubic | Set Size | 2221.2 | 1 | 2221.2 | 0.51 | 0.481 |
| | Error | 42386.4 | 24 | 1766.1 | | |
| | | Subtraction Identity-Match | | | | |
| Linear | Set Size | 2734675.5 | 1 | 2734675.5 | 26.98 | <0.001 |
| | Error | 2432759.1 | 24 | 101364.9 | | |
| Quadratic | Set Size | 2585.7 | 1 | 2585.7 | 0.17 | 0.681 |
| | Error | 358201.6 | 24 | 14925.1 | | |
| Cubic | Set Size | 51690.3 | 1 | 51690.3 | 2.08 | 0.163 |
| | Error | 597486.7 | 24 | 24895.3 | | |
| | | Class Exemplar Categorization-Match | | | | |
| Linear | Set Size | 326129.9 | 1 | 326129.9 | 1.54 | 0.227 |
| | Error | 5090104.6 | 24 | 212087.7 | | |
| Quadratic | Set Size | 3094.5 | 1 | 3094.5 | 0.07 | 0.799 |
| | Error | 1119615.7 | 24 | 46650.7 | | |
| Cubic | Set Size | 1942.9 | 1 | 1942.9 | 0.04 | 0.844 |
| | Error | 1172511.8 | 24 | 48854.7 | | |

Appendix E. *Statistical Analyses of Slope and Intercept Estimates for CHI and Normal Subjects on the Nine Tasks.*

### Motor Programming

Independent Samples T-Test

*Slope analysis*

| | Mean | SD |
|---|---|---|
| CHI group | 136.61 | 98.05 |
| Control group | 61.19 | 46.96 |

Pooled variances $t(24) = 2.501$, $p = 0.02$

*Intercept analysis*

| | | |
|---|---|---|
| CHI group | 601.56 | 174.95 |
| Control group | 646.81 | 201.90 |

Pooled variances $t(24) = -0.611$, $p = 0.547$

### Consonant Simultaneous Identity-Match

*Slope analysis*

| Between Subjects | SS | DF | MS | F | P |
|---|---|---|---|---|---|
| Group | 25843.0 | 1 | 25843.0 | 22.128 | <0.001 |
| Error | 28029.4 | 24 | 1167.9 | | |
| Within Subjects | | | | | |
| Probe | 2217.0 | 1 | 2217.0 | 10.828 | 0.003 |
| Probe x Group | 861.1 | 1 | 861.1 | 4.206 | 0.050 |
| Error | 4913.9 | 24 | 204.7 | | |

*Intercept analysis*

| | | | | | |
|---|---|---|---|---|---|
| Between Subjects | | | | | |
| Group | 30363.6 | 1 | 30363.6 | 2.963 | 0.098 |
| Error | 245935.9 | 24 | 10247.3 | | |
| Within Subjects | | | | | |
| Probe | 20210.0 | 1 | 20210.0 | 16.597 | <0.001 |
| Probe x Group | 7810.7 | 1 | 7810.7 | 6.414 | 0.018 |
| Error | 29225.0 | 24 | 1217.7 | | |

Pattern Simultaneous Identity Match

| | | | | | |
|---|---|---|---|---|---|
| Slope analysis | | | | | |
| Between Subjects | SS | DF | MS | F | P |
| Group | 76900.5 | 1 | 76900.5 | 14.018 | 0.001 |
| Error | 131657.9 | 24 | 5485.7 | | |
| Within Subjects | | | | | |
| Probe | 1883.3 | 1 | 1883.3 | 3.595 | 0.070 |
| Probe x Group | 2364.0 | 1 | 2364.0 | 4.513 | 0.044 |
| Error | 12572.9 | 24 | 523.9 | | |
| Intercept analysis | | | | | |
| Between Subjects | | | | | |
| Group | 261168.0 | 1 | 261168.0 | 7.497 | 0.011 |
| Error | 836038.3 | 24 | 34835.0 | | |
| Within Subjects | | | | | |
| Probe | 2245.4 | 1 | 2245.4 | 0.554 | 0.464 |
| Probe x Group | 2164.6 | 1 | 2164.6 | 0.534 | 0.472 |
| Error | 97220.3 | 24 | 4050.8 | | |

Number Simultaneous Identity Match

| | | | | | |
|---|---|---|---|---|---|
| Slope analysis | | | | | |
| Between Subjects | SS | DF | MS | F | P |
| Group | 2445.2 | 1 | 2445.2 | 2.075 | 0.163 |
| Error | 28278.0 | 24 | 1178.3 | | |
| Within Subjects | | | | | |
| Probe | 10032.7 | 1 | 10032.7 | 17.485 | <0.001 |
| Probe x Group | 2930.5 | 1 | 2930.5 | 5.107 | 0.033 |
| Error | 13771.0 | 24 | 573.8 | | |
| Intercept analysis | | | | | |
| Between Subjects | | | | | |
| Group | 262770.0 | 1 | 262770.0 | 18.547 | <0.001 |
| Error | 340021.1 | 24 | 14167.5 | | |
| Within Subjects | | | | | |
| Probe | 1087.1 | 1 | 1087.1 | 0.456 | 0.506 |
| Probe x Group | 9.2 | 1 | 9.2 | 0.004 | 0.951 |
| Error | 57215.1 | 24 | 2384.0 | | |

Word Simultaneous Identity-Match

| Slope analysis | | | | | |
|---|---|---|---|---|---|
| Between Subjects | SS | DF | MS | F | P |
| Group | 124059.9 | 1 | 124059.9 | 15.962 | 0.001 |
| Error | 186531.1 | 24 | 7772.1 | | |
| Within Subjects | | | | | |
| Probe | 6020.8 | 1 | 6020.8 | 5.095 | 0.033 |
| Probe x Group | 6444.8 | 1 | 6444.8 | 5.454 | 0.028 |
| Error | 28359.2 | 24 | 1181.6 | | |
| Intercept analysis | | | | | |
| Between Subjects | | | | | |
| Group | 15400.1 | 1 | 15400.1 | 0.443 | 0.512 |
| Error | 833767.1 | 24 | 34740.3 | | |
| Within Subjects | | | | | |
| Probe | 701.0 | 1 | 701.0 | 0.199 | 0.659 |
| Probe x Group | 998.1 | 1 | 998.1 | 0.284 | 0.599 |
| Error | 84490.7 | 24 | 3520.4 | | |

Consonant Delayed Identity-Match

| Slope analysis | | | | | |
|---|---|---|---|---|---|
| Between Subjects | SS | DF | MS | F | P |
| Group | 24866.8 | 1 | 24866.8 | 25.923 | <0.001 |
| Error | 23022.6 | 24 | 959.3 | | |
| Within Subjects | | | | | |
| Probe | 1446.6 | 1 | 1446.6 | 7.399 | 0.012 |
| Probe x Group | 1235.2 | 1 | 1235.2 | 6.318 | 0.019 |
| Error | 4692.5 | 24 | 195.5 | | |
| Intercept analysis | | | | | |
| Between Subjects | | | | | |
| Group | 49154.5 | 1 | 49154.5 | 4.842 | 0.038 |
| Error | 243651.0 | 24 | 10152.1 | | |
| Within Subjects | | | | | |
| Probe | 4289.4 | 1 | 4289.4 | 2.411 | 0.134 |
| Probe x Group | 7712.1 | 1 | 7712.1 | 4.334 | 0.048 |
| Error | 42703.0 | 24 | 1779.3 | | |

Pattern Delayed Identity-Match

| Slope analysis | | | | | |
|---|---|---|---|---|---|
| Between Subjects | SS | DF | MS | F | P |
| Group | 19042.8 | 1 | 19042.8 | 14.849 | 0.001 |
| Error | 30778.7 | 24 | 1282.4 | | |
| Within Subjects | | | | | |
| Probe | 737.9 | 1 | 737.9 | 0.566 | 0.459 |
| Probe x Group | 383.1 | 1 | 383.1 | 0.294 | 0.593 |
| Error | 31315.6 | 24 | 1304.8 | | |
| Intercept analysis | | | | | |
| Between Subjects | | | | | |
| Group | 2443.1 | 1 | 2443.1 | 0.397 | 0.534 |
| Error | 147565.8 | 24 | 6148.6 | | |
| Within Subjects | | | | | |
| Probe | 692.8 | 1 | 692.8 | 0.139 | 0.713 |
| Probe x Group | 216.5 | 1 | 216.5 | 0.043 | 0.837 |
| Error | 119861.2 | 24 | 4994.2 | | |

Subtraction Identity-Match

| Slope analysis | | | | | |
|---|---|---|---|---|---|
| Between Subjects | SS | DF | MS | F | P |
| Group | 46891.4 | 1 | 46891.4 | 2.313 | 0.141 |
| Error | 486551.8 | 24 | 20272.9 | | |
| Within Subjects | | | | | |
| Probe | 61213.8 | 1 | 61213.8 | 38.923 | <0.001 |
| Probe x Group | 25378.9 | 1 | 25378.9 | 16.137 | 0.001 |
| Error | 37744.5 | 24 | 1572.7 | | |
| Intercept analysis | | | | | |
| Between Subjects | | | | | |
| Group | 2854192.7 | 1 | 2854192.7 | 7.498 | 0.011 |
| Error | 9135475.3 | 24 | 380644.8 | | |
| Within Subjects | | | | | |
| Probe | 31327.1 | 1 | 31327.1 | 1.441 | 0.242 |
| Probe x Group | 4108.9 | 1 | 4108.9 | 0.189 | 0.668 |
| Error | 521761.6 | 24 | 21740.1 | | |

| Class Exemplar Categorization Identity-Match | | | | | |
|---|---|---|---|---|---|
| Slope analysis | | | | | |
| Between Subjects | SS | DF | MS | F | P |
| Group | 1801369.3 | 1 | 1801369.3 | 42.468 | <0.001 |
| Error | 1018020.9 | 24 | 42417.5 | | |
| Within Subjects | | | | | |
| Probe | 83655.6 | 1 | 83655.6 | 2.059 | 0.164 |
| Probe x Group | 54159.9 | 1 | 54159.9 | 1.333 | 0.260 |
| Error | 975203.0 | 24 | 40633.5 | | |
| Intercept analysis | | | | | |
| Between Subjects | | | | | |
| Group | 246080.7 | 1 | 246080.7 | 1.841 | 0.188 |
| Error | 3208656.4 | 24 | 133694.0 | | |
| Within Subjects | | | | | |
| Probe | 1566173.1 | 1 | 1566173.1 | 10.110 | 0.004 |
| Probe x Group | 960927.9 | 1 | 960927.9 | 6.203 | 0.020 |
| Error | 3717902.1 | 24 | 154912.6 | | |

Comparison of Consonant Simultaneous and Delayed Identity-Match Tasks

| Slope analysis | | | | | |
|---|---|---|---|---|---|
| Between Subjects | SS | DF | MS | F | P |
| Group | 50705.1 | 1 | 50705.1 | 29.519 | <0.001 |
| Error | 41225.7 | 24 | 1717.7 | | |
| Within Subjects | | | | | |
| Task | 15.3 | 1 | 15.3 | 0.037 | 0.848 |
| Task x Group | 4.7 | 1 | 4.7 | 0.011 | 0.916 |
| Error | 9826.2 | 24 | 409.4 | | |
| Probe | 40.9 | 1 | 40.9 | 0.205 | 0.655 |
| Probe x Group | 16.8 | 1 | 16.8 | 0.084 | 0.774 |
| Error | 4792.5 | 24 | 199.7 | | |
| Task x Probe | 3622.6 | 1 | 3622.6 | 18.061 | <0.001 |
| Task x Probe x Group | 2079.5 | 1 | 2079.5 | 10.367 | 0.004 |
| Error | 4813.9 | 24 | 200.6 | | |
| Intercept analysis | | | | | |
| Between Subjects | SS | DF | MS | F | P |
| Group | 78391.9 | 1 | 78391.9 | 6.378 | 0.019 |
| Error | 294975.4 | 24 | 12290.6 | | |
| Within Subjects | | | | | |
| Task | 1741.2 | 1 | 1741.2 | 0.215 | 0.647 |
| Task x Group | 1126.1 | 1 | 1126.1 | 0.139 | 0.713 |
| Error | 194611.5 | 24 | 8108.8 | | |
| Probe | 2938.9 | 1 | 2938.9 | 2.671 | 0.115 |
| Probe x Group | 0.157 | 1 | 0.157 | <0.001 | 0.991 |
| Error | 26412.2 | 24 | 1100.5 | | |
| Task x Probe | 21560.5 | 1 | 21560.5 | 11.369 | 0.003 |
| Task x Probe x Group | 15522.7 | 1 | 15522.7 | 8.185 | 0.009 |
| Error | 45515.9 | 24 | 1896.5 | | |

Comparison of Pattern Simultaneous and Delayed Identity-Match Tasks

| <u>Slope analysis</u> | | | | | |
|---|---|---|---|---|---|
| Between Subjects | SS | DF | MS | F | P |
| Group | 86239.1 | 1 | 86239.1 | 23.756 | <0.001 |
| Error | 87124.7 | 24 | 3630.2 | | |
| Within Subjects | | | | | |
| Task | 19627.6 | 1 | 19627.6 | 6.255 | 0.020 |
| Task x Group | 9704.1 | 1 | 9704.1 | 3.092 | 0.091 |
| Error | 75311.8 | 24 | 3137.9 | | |
| Probe | 2489.4 | 1 | 2489.4 | 2.136 | 0.157 |
| Probe x Group | 2325.2 | 1 | 2325.2 | 1.995 | 0.171 |
| Error | 27970.5 | 24 | 1165.4 | | |
| Task x Probe | 131.7 | 1 | 131.7 | 0.199 | 0.660 |
| Task x Probe x Group | 421.9 | 1 | 421.9 | 0.636 | 0.433 |
| Error | 15918.1 | 24 | 663.2 | | |
| <u>Intercept analysis</u> | | | | | |
| Between Subjects | SS | DF | MS | F | P |
| Group | 106545.9 | 1 | 106545.9 | 5.267 | 0.031 |
| Error | 485535.3 | 24 | 20230.6 | | |
| Within Subjects | | | | | |
| Task | 108625.5 | 1 | 108625.5 | 5.234 | 0.031 |
| Task x Group | 157065.1 | 1 | 157065.1 | 7.568 | 0.011 |
| Error | 498068.7 | 24 | 20752.9 | | |
| Probe | 2716.4 | 1 | 2716.4 | 0.531 | 0.473 |
| Probe x Group | 505.9 | 1 | 505.9 | 0.099 | 0.756 |
| Error | 122887.6 | 24 | 5120.3 | | |
| Task x Probe | 221.8 | 1 | 221.8 | 0.057 | 0.814 |
| Task x Probe x Group | 1875.1 | 1 | 1875.1 | 0.478 | 0.496 |
| Error | 94193.9 | 24 | 3924.7 | | |

Comparison of Categorization and Word Simultaneous Identity-Match Tasks

Slope analysis

| Between Subjects | S S | DF | M S | F | P |
|---|---|---|---|---|---|
| Group | 1435448.9 | 1 | 1435448.9 | 37.107 | <0.001 |
| Error | 928417.7 | 24 | 38684.1 | | |
| Within Subjects | | | | | |
| Task | 801598.8 | 1 | 801598.8 | 69.670 | <0.001 |
| Task x Group | 489980.2 | 1 | 489980.2 | 42.586 | <0.001 |
| Error | 276134.2 | 24 | 11505.5 | | |
| Probe | 22395.5 | 1 | 22395.5 | 1.188 | 0.287 |
| Probe x Group | 11619.4 | 1 | 11619.4 | 0.616 | 0.440 |
| Error | 452435.9 | 24 | 18851.5 | | |
| Task x Probe | 67280.7 | 1 | 67280.7 | 2.930 | 0.100 |
| Task x Probe x Group | 48985.2 | 1 | 48985.2 | 2.133 | 0.157 |
| Error | 551126.2 | 24 | 22963.5 | | |

Intercept analysis

| Between Subjects | S S | DF | M S | F | P |
|---|---|---|---|---|---|
| Group | 192300.6 | 1 | 192300.6 | 1.793 | 0.193 |
| Error | 2573313.5 | 24 | 107221.4 | | |
| Within Subjects | | | | | |
| Task | 767.1 | 1 | 767.1 | 0.013 | 0.912 |
| Task x Group | 69180.2 | 1 | 69180.2 | 1.130 | 0.298 |
| Error | 1469109.9 | 24 | 61212.9 | | |
| Probe | 816570.5 | 1 | 816570.5 | 12.315 | 0.002 |
| Probe x Group | 449993.9 | 1 | 449993.9 | 6.787 | 0.016 |
| Error | 1591340.6 | 24 | 66305.9 | | |
| Task x Probe | 750303.6 | 1 | 750303.6 | 8.144 | 0.009 |
| Task x Probe x Group | 511932.1 | 1 | 511932.1 | 5.557 | 0.027 |
| Error | 2211052.1 | 24 | 92127.2 | | |

Comparison of Subtraction and Number Simultaneous Identity-Match Tasks

Slope analysis

| Between Subjects | SS | DF | MS | F | P |
|---|---|---|---|---|---|
| Group | 35376.2 | 1 | 35376.2 | 3.223 | 0.085 |
| Error | 263424.7 | 24 | 10976.0 | | |
| Within Subjects | | | | | |
| Task | 51142.9 | 1 | 51142.9 | 4.882 | 0.037 |
| Task x Group | 13960.4 | 1 | 13960.4 | 1.333 | 0.260 |
| Error | 251405.1 | 24 | 10475.2 | | |
| Probe | 60405.0 | 1 | 60405.0 | 52.122 | <0.001 |
| Probe x Group | 22778.7 | 1 | 22778.7 | 19.655 | <0.001 |
| Error | 27814.2 | 24 | 1158.9 | | |
| Task x Probe | 10841.4 | 1 | 10841.4 | 10.978 | 0.003 |
| Task x Probe x Group | 5530.6 | 1 | 5530.6 | 5.600 | 0.026 |
| Error | 23701.1 | 24 | 987.5 | | |

Intercept analysis

| Between Subjects | SS | DF | MS | F | P |
|---|---|---|---|---|---|
| Group | 2424504.5 | 1 | 2424504.5 | 11.404 | 0.002 |
| Error | 5102315.6 | 24 | 212596.5 | | |
| Within Subjects | | | | | |
| Task | 1355782.0 | 1 | 1355782.0 | 7.441 | 0.012 |
| Task x Group | 692458.2 | 1 | 692458.2 | 3.800 | 0.063 |
| Error | 4373180.8 | 24 | 182215.9 | | |
| Probe | 22042.8 | 1 | 22042.8 | 7.792 | 0.193 |
| Probe x Group | 2253.6 | 1 | 2253.6 | 0.183 | 0.672 |
| Error | 295244.9 | 24 | 12301.9 | | |
| Task x Probe | 10371.3 | 1 | 10371.3 | 0.877 | 0.358 |
| Task x Probe x Group | 1864.5 | 1 | 1864.5 | 0.158 | 0.695 |
| Error | 283731.8 | 24 | 11822.2 | | |

Comparison of Simultaneous Identity-Match Tasks

Slope analysis

| Between Subjects | SS | DF | MS | F | P |
|---|---|---|---|---|---|
| Group | 176289.7 | 1 | 176289.7 | 23.987 | <0.001 |
| Error | 177048.8 | 24 | 7377.0 | | |
| Within Subjects | | | | | |
| Task | 63834.4 | 3 | 21278.1 | 7.759 | <0.001 |
| Task x Group | 52958.9 | 3 | 17652.9 | 6.437 | 0.001 |
| Error | 197447.6 | 72 | 2742.3 | | |
| Probe | 1904.2 | 1 | 1904.2 | 5.514 | 0.027 |
| Probe x Group | 796.6 | 1 | 796.6 | 2.307 | 0.142 |
| Error | 8288.2 | 24 | 345.3 | | |
| Task x Probe | 18249.4 | 3 | 6083.2 | 8.533 | <0.001 |
| Task x Probe x Group | 11803.9 | 3 | 3934.6 | 5.519 | 0.002 |
| Error | 51328.7 | 72 | 712.9 | | |

Intercept analysis

| Between Subjects | SS | DF | MS | F | P |
|---|---|---|---|---|---|
| Group | 22020.1 | 1 | 22020.1 | 0.537 | 0.471 |
| Error | 983265.1 | 24 | 40969.4 | | |
| Within Subjects | | | | | |
| Task | 132360.2 | 3 | 44120.1 | 2.496 | 0.067 |
| Task x Group | 547681.5 | 3 | 182560.5 | 10.330 | <0.001 |
| Error | 1272497.3 | 72 | 17673.6 | | |
| Probe | 8376.9 | 1 | 8376.9 | 11.307 | 0.003 |
| Probe x Group | 2513.7 | 1 | 2513.7 | 3.393 | 0.078 |
| Error | 17781.4 | 24 | 740.9 | | |
| Task x Probe | 15866.5 | 3 | 5288.8 | 1.521 | 0.216 |
| Task x Probe x Group | 8468.8 | 3 | 2822.9 | 0.812 | 0.491 |
| Error | 250369.7 | 72 | 3477.4 | | |

Comparison of Delayed Identity-Match Tasks

| | SS | DF | MS | F | P |
|---|---|---|---|---|---|
| Slope analysis | | | | | |
| Between Subjects | SS | DF | MS | F | P |
| Group | 43715.6 | 1 | 43715.6 | 36.686 | <0.001 |
| Error | 28599.0 | 24 | 1191.6 | | |
| Within Subjects | | | | | |
| Task | 1290.8 | 1 | 1290.8 | 1.229 | 0.279 |
| Task x Group | 193.9 | 1 | 193.9 | 0.185 | 0.671 |
| Error | 25202.2 | 24 | 1050.1 | | |
| Probe | 59.1 | 1 | 59.1 | 0.069 | 0.795 |
| Probe x Group | 121.2 | 1 | 121.2 | 0.142 | 0.709 |
| Error | 20465.9 | 24 | 852.7 | | |
| Task x Probe | 2125.4 | 1 | 2125.4 | 3.282 | 0.083 |
| Task x Probe x Group | 1497.0 | 1 | 1497.0 | 2.312 | 0.141 |
| Error | 15542.2 | 24 | 647.5 | | |
| Intercept analysis | | | | | |
| Between Subjects | SS | DF | MS | F | P |
| Group | 14840.3 | 1 | 14840.3 | 1.594 | 0.219 |
| Error | 223413.7 | 24 | 9308.9 | | |
| Within Subjects | | | | | |
| Task | 34268.9 | 1 | 34268.9 | 4.901 | 0.037 |
| Task x Group | 36757.2 | 1 | 36757.2 | 5.257 | 0.031 |
| Error | 167803.0 | 24 | 6991.8 | | |
| Probe | 767.2 | 1 | 767.2 | 0.182 | 0.673 |
| Probe x Group | 5256.5 | 1 | 5256.5 | 1.249 | 0.275 |
| Error | 101025.2 | 24 | 4209.4 | | |
| Task x Probe | 4215.1 | 1 | 4215.1 | 1.644 | 0.212 |
| Task x Probe x Group | 2672.1 | 1 | 2672.1 | 1.042 | 0.318 |
| Error | 61539.1 | 24 | 2564.1 | | |

## Comparison of Transformation Tasks

### Slope analysis

| Between Subjects | S S | DF | MS | F | P |
|---|---|---|---|---|---|
| Group | 1214765.2 | 1 | 1214765.2 | 47.611 | <0.001 |
| Error | 612339.3 | 24 | 25514.1 | | |
| Within Subjects | | | | | |
| Task | 728751.7 | 1 | 728751.7 | 19.603 | <0.001 |
| Task x Group | 633495.4 | 1 | 633495.4 | 17.040 | <0.001 |
| Error | 892233.5 | 24 | 37176.4 | | |
| Probe | 874.4 | 1 | 874.4 | 0.039 | 0.845 |
| Probe x Group | 2694.9 | 1 | 2694.9 | 0.120 | 0.732 |
| Error | 540010.9 | 24 | 22500.5 | | |
| Task x Probe | 143995.0 | 1 | 143995.0 | 7.307 | 0.012 |
| Task x Probe x Group | 76843.9 | 1 | 76843.9 | 3.900 | 0.060 |
| Error | 472936.5 | 24 | 19705.7 | | |

### Intercept analysis

| Between Subjects | S S | DF | MS | F | P |
|---|---|---|---|---|---|
| Group | 712066.4 | 1 | 712066.4 | 2.577 | 0.122 |
| Error | 6632795.9 | 24 | 276366.5 | | |
| Within Subjects | | | | | |
| Task | 2813274.4 | 1 | 2813274.4 | 11.822 | 0.002 |
| Task x Group | 2388207.1 | 1 | 2388207.1 | 10.036 | 0.004 |
| Error | 5711335.8 | 24 | 237972.3 | | |
| Probe | 577247.0 | 1 | 577247.0 | 6.136 | 0.021 |
| Probe x Group | 419682.5 | 1 | 419682.5 | 4.461 | 0.045 |
| Error | 2257725.4 | 24 | 94071.9 | | |
| Task x Probe | 1020253.1 | 1 | 1020253.1 | 12.355 | 0.002 |
| Task x Probe x Group | 545354.3 | 1 | 545354.3 | 6.604 | 0.017 |
| Error | 1981938.3 | 24 | 82580.7 | | |

Appendix F-1. Individual Subject Slope and Intercept Estimates for the Motor Programming Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| CHI.1 | 11.9 | 749.1 | N.1 | 16.5 | 401.7 |
| CHI.2 | 175.2 | 621.4 | N.2 | 3.0 | 443.0 |
| CHI.3 | 70.5 | 673.6 | N.3 | 140.5 | 789.4 |
| CHI.4 | 62.2 | 264.3 | N.4 | 21.0 | 347.7 |
| CHI.5 | 160.8 | 640.3 | N.5 | 127.5 | 347.1 |
| CHI.6 | 267.5 | 407.9 | N.6 | 115.1 | 846.8 |
| CHI.7 | 52.9 | 674.2 | N.7 | 78.6 | 773.6 |
| CHI.8 | 194.5 | 479.4 | N.8 | 35.7 | 886.0 |
| CHI.9 | 75.6 | 662.7 | N.9 | 27.5 | 721.7 |
| CHI.10 | 274.7 | 747.5 | N.10 | 58.3 | 530.1 |
| CHI.11 | 9.7 | 765.6 | N.11 | 14.0 | 753.4 |
| CHI.12 | 283.1 | 329.9 | N.12 | 57.3 | 840.5 |
| CHI.13 | 137.4 | 804.7 | N.13 | 100.5 | 757.4 |
| Mean | 136.6 | 601.6 | | 61.2 | 646.8 |
| SD | 98.0 | 175.0 | | 47.0 | 201.9 |

Appendix F-2. Individual Subject Slope and Intercept Estimates for the Consonant Simultaneous Identity-Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| | | Positive Probe Trials | | | |
| CHI.1 | 122.8 | 204.5 | N.1 | 26.3 | 429.5 |
| CHI.2 | 114.5 | 242.1 | N.2 | 40.8 | 406.0 |
| CHI.3 | 99.8 | 276.7 | N.3 | 45.9 | 464.0 |
| CHI.4 | 57.4 | 348.6 | N.4 | 29.9 | 270.0 |
| CHI.5 | 56.0 | 370.2 | N.5 | 57.7 | 298.8 |
| CHI.6 | 170.8 | 143.6 | N.6 | 16.8 | 442.5 |
| CHI.7 | 90.6 | 272.5 | N.7 | 38.9 | 347.5 |
| CHI.8 | 112.8 | 280.5 | N.8 | 39.0 | 235.0 |
| CHI.9 | 52.8 | 312.7 | N.9 | 35.4 | 424.8 |
| CHI.10 | 54.0 | 343.0 | N.10 | 55.7 | 292.3 |
| CHI.11 | 90.6 | 254.3 | N.11 | 16.9 | 366.1 |
| CHI.12 | 77.6 | 286.9 | N.12 | 32.8 | 262.3 |
| CHI.13 | 82.5 | 278.7 | N.13 | 60.6 | 322.5 |
| Mean | 90.9 | 278.0 | | 38.2 | 350.9 |
| SD | 34.1 | 60.8 | | 14.2 | 76.8 |
| | | Negative Probe Trials | | | |
| CHI.1 | 36.7 | 405.1 | N.1 | 26.3 | 465.0 |
| CHI.2 | 90.7 | 379.0 | N.2 | 40.8 | 463.0 |
| CHI.3 | 79.2 | 344.7 | N.3 | 45.9 | 504.0 |
| CHI.4 | 24.2 | 451.1 | N.4 | 29.9 | 277.0 |
| CHI.5 | 16.2 | 485.5 | N.5 | 57.8 | 378.4 |
| CHI.6 | 142.8 | 230.5 | N.6 | 16.8 | 417.1 |
| CHI.7 | 80.5 | 309.7 | N.7 | 38.9 | 349.2 |
| CHI.8 | 92.9 | 286.0 | N.8 | 39.0 | 246.5 |
| CHI.9 | 57.2 | 318.8 | N.9 | 35.4 | 513.8 |
| CHI.10 | 18.7 | 442.5 | N.10 | 55.7 | 360.7 |
| CHI.11 | 63.4 | 296.1 | N.11 | 16.9 | 335.0 |
| CHI.12 | 78.3 | 324.1 | N.12 | 32.8 | 311.5 |
| CHI.13 | 76.3 | 325.1 | N.13 | 55.0 | 286.5 |
| Mean | 65.9 | 353.7 | | 29.5 | 377.5 |
| SD | 35.7 | 74.2 | | 10.5 | 88.5 |

Appendix F-3. Individual Subject Slope and Intercept Estimates for the Pattern Simultaneous Identity-Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| | | Positive Probe Trials | | | |
| CHI.1 | 127.6 | 404.8 | N.1 | 70.9 | 416.5 |
| CHI.2 | 208.0 | 104.0 | N.2 | 33.9 | 580.5 |
| CHI.3 | 116.5 | 317.6 | N.3 | 98.1 | 442.0 |
| CHI.4 | 79.4 | 491.1 | N.4 | 53.5 | 570.0 |
| CHI.5 | 130.3 | 276.4 | N.5 | 43.9 | 594.5 |
| CHI.6 | 234.3 | 445.8 | N.6 | 27.9 | 613.0 |
| CHI.7 | 91.1 | 327.1 | N.7 | 54.9 | 535.5 |
| CHI.8 | 92.6 | 455.4 | N.8 | 59.6 | 280.1 |
| CHI.9 | 148.5 | 148.7 | N.9 | 54.5 | 383.1 |
| CHI.10 | 56.8 | 521.4 | N.10 | 106.6 | 295.9 |
| CHI.11 | 207.0 | 148.5 | N.11 | 85.7 | 429.7 |
| CHI.12 | 286.1 | 0.8 | N.12 | 89.3 | 244.1 |
| CHI.13 | 281.0 | 75.5 | N.13 | 105.3 | 342.4 |
| Mean | 158.4 | 285.9 | | 68.0 | 440.6 |
| SD | 76.9 | 174.4 | | 26.7 | 128.3 |
| | | Negative Probe Trials | | | |
| CHI.1 | 137.5 | 282.0 | N.1 | 78.8 | 434.5 |
| CHI.2 | 129.8 | 255.0 | N.2 | 53.4 | 590.0 |
| CHI.3 | 97.3 | 393.5 | N.3 | 89.6 | 479.0 |
| CHI.4 | 91.2 | 428.1 | N.4 | 73.8 | 558.5 |
| CHI.5 | 71.2 | 407.6 | N.5 | 40.1 | 615.5 |
| CHI.6 | 224.8 | 392.8 | N.6 | 74.6 | 533.0 |
| CHI.7 | 102.2 | 380.2 | N.7 | 68.5 | 535.0 |
| CHI.8 | 159.7 | 306.6 | N.8 | 62.4 | 315.6 |
| CHI.9 | 90.5 | 309.7 | N.9 | 86.1 | 345.1 |
| CHI.10 | 107.2 | 361.3 | N.10 | 108.1 | 384.6 |
| CHI.11 | 158.9 | 262.8 | N.11 | 120.7 | 322.3 |
| CHI.12 | 263.7 | 63.0 | N.12 | 103.8 | 222.2 |
| CHI.13 | 281.0 | 79.2 | N.13 | 130.6 | 261.4 |
| Mean | 147.3 | 301.7 | | 83.9 | 430.5 |
| SD | 68.6 | 117.0 | | 26.3 | 131.1 |

Appendix F-4. Individual Subject Slope and Intercept Estimates for the Number Simultaneous Identity-Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| | | Positive Probe Trials | | | |
| CHI.1 | 76.2 | 425.9 | N.1 | 57.2 | 500.5 |
| CHI.2 | 47.0 | 518.9 | N.2 | 75.2 | 409.5 |
| CHI.3 | 67.4 | 503.9 | N.3 | 85.7 | 409.0 |
| CHI.4 | 93.6 | 359.0 | N.4 | 58.2 | 229.7 |
| CHI.5 | 86.7 | 504.8 | N.5 | 91.7 | 309.7 |
| CHI.6 | 100.3 | 278.9 | N.6 | 80.5 | 174.9 |
| CHI.7 | 42.1 | 513.8 | N.7 | 55.1 | 224.7 |
| CHI.8 | 103.1 | 306.5 | N.8 | 148.1 | 165.7 |
| CHI.9 | 73.5 | 439.4 | N.9 | 118.4 | 220.1 |
| CHI.10 | 106.6 | 338.5 | N.10 | 69.4 | 194.8 |
| CHI.11 | 105.3 | 382.1 | N.11 | 146.8 | 123.0 |
| CHI.12 | 76.5 | 407.4 | N.12 | 49.2 | 341.2 |
| CHI.13 | 91.4 | 417.9 | N.13 | 51.0 | 235.3 |
| Mean | 82.3 | 415.2 | | 83.6 | 272.1 |
| SD | 21.1 | 80.5 | | 34.3 | 112.9 |
| | | Negative Probe Trials | | | |
| CHI.1 | 115.4 | 410.3 | N.1 | 106.4 | 432.5 |
| CHI.2 | 157.8 | 397.4 | N.2 | 139.9 | 314.5 |
| CHI.3 | 143.4 | 476.3 | N.3 | 108.1 | 413.5 |
| CHI.4 | 120.9 | 371.0 | N.4 | 91.9 | 178.4 |
| CHI.5 | 104.8 | 473.7 | N.5 | 134.2 | 239.8 |
| CHI.6 | 187.5 | 356.4 | N.6 | 83.8 | 176.7 |
| CHI.7 | 138.9 | 441.0 | N.7 | 98.5 | 165.5 |
| CHI.8 | 98.5 | 447.2 | N.8 | 154.3 | 206.4 |
| CHI.9 | 159.4 | 299.8 | N.9 | 112.8 | 235.3 |
| CHI.10 | 83.5 | 392.4 | N.10 | 112.2 | 162.5 |
| CHI.11 | 178.4 | 277.4 | N.11 | 151.6 | 192.2 |
| CHI.12 | 167.0 | 330.1 | N.12 | 53.1 | 354.8 |
| CHI.13 | 165.8 | 370.1 | N.13 | 101.1 | 133.6 |
| Mean | 140.1 | 387.9 | | 111.4 | 246.6 |
| SD | 32.9 | 62.6 | | 28.3 | 99.8 |

Appendix F-5. Individual Subject Slope and Intercept Estimates for the Word Simultaneous Identity-Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| | | Positive Probe Trials | | | |
| CHI.1 | 93.9 | 273.0 | N.1 | 68.7 | 364.0 |
| CHI.2 | 149.0 | 236.5 | N.2 | -3.0 | 752.5 |
| CHI.3 | 102.9 | 287.3 | N.3 | 123.7 | 257.0 |
| CHI.4 | 95.6 | 214.3 | N.4 | 36.7 | 255.9 |
| CHI.5 | 95.9 | 358.8 | N.5 | 76.9 | 210.3 |
| CHI.6 | 309.7 | 50.0 | N.6 | 21.8 | 245.0 |
| CHI.7 | 101.6 | 297.5 | N.7 | 78.0 | 220.1 |
| CHI.8 | 219.4 | 256.7 | N.8 | 20.5 | 272.1 |
| CHI.9 | 61.5 | 462.5 | N.9 | 34.5 | 231.5 |
| CHI.10 | 94.1 | 236.1 | N.10 | 60.2 | 256.4 |
| CHI.11 | 77.0 | 379.0 | N.11 | 21.3 | 228.2 |
| CHI.12 | 154.7 | 119.9 | N.12 | 31.1 | 220.1 |
| CHI.13 | 133.2 | 167.5 | N.13 | 137.5 | 99.4 |
| Mean | 129.9 | 256.8 | | 54.5 | 282.5 |
| SD | 67.8 | 109.0 | | 41.7 | 152.8 |
| | | Negative Probe Trials | | | |
| CHI.1 | 55.0 | 403.5 | N.1 | 51.8 | 425.0 |
| CHI.2 | 162.1 | 297.5 | N.2 | -42.3 | 838.0 |
| CHI.3 | 118.2 | 339.1 | N.3 | 89.4 | 354.5 |
| CHI.4 | 201.5 | 265.5 | N.4 | 15.9 | 304.8 |
| CHI.5 | 218.0 | 183.2 | N.5 | 50.0 | 271.6 |
| CHI.6 | 431.5 | -4.9 | N.6 | 7.9 | 307.3 |
| CHI.7 | 132.5 | 360.5 | N.7 | 70.4 | 302.1 |
| CHI.8 | 202.4 | 257.9 | N.8 | 20.6 | 272.2 |
| CHI.9 | 29.0 | 433.2 | N.9 | 21.3 | 263.3 |
| CHI.10 | 82.0 | 398.4 | N.10 | 89.6 | 209.5 |
| CHI.11 | 125.6 | 373.5 | N.11 | 30.1 | 312.4 |
| CHI.12 | 144.5 | 142.7 | N.12 | 12.4 | 283.1 |
| CHI.13 | 92.1 | 418.7 | N.13 | 17.9 | 286.1 |
| Mean | 153.4 | 297.6 | | 33.4 | 340.8 |
| SD | 101.2 | 128.2 | | 36.5 | 157.7 |

Appendix F-6. Individual Subject Slope and Intercept Estimates for the Consonant Delayed Identity-Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| | | Positive Probe Trials | | | |
| CHI.1 | 41.0 | 396.8 | N.1 | 41.7 | 433.5 |
| CHI.2 | 83.3 | 399.0 | N.2 | 32.4 | 414.5 |
| CHI.3 | 91.0 | 282.7 | N.3 | 39.0 | 428.5 |
| CHI.4 | 49.1 | 311.3 | N.4 | 24.7 | 456.0 |
| CHI.5 | 70.6 | 256.9 | N.5 | 40.4 | 403.5 |
| CHI.6 | 92.2 | 335.7 | N.6 | 58.6 | 367.0 |
| CHI.7 | 52.6 | 340.6 | N.7 | 26.3 | 332.4 |
| CHI.8 | 79.1 | 394.1 | N.8 | 31.8 | 269.4 |
| CHI.9 | 45.7 | 280.8 | N.9 | 41.0 | 251.2 |
| CHI.10 | 35.1 | 330.2 | N.10 | 27.6 | 211.0 |
| CHI.11 | 44.4 | 340.2 | N.11 | 28.9 | 351.4 |
| CHI.12 | 109.4 | 171.5 | N.12 | 35.9 | 325.1 |
| CHI.13 | 116.6 | 158.0 | N.13 | 39.0 | 236.8 |
| Mean | 69.9 | 307.5 | | 35.9 | 344.6 |
| SD | 27.3 | 77.5 | | 9.0 | 81.9 |
| | | Negative Probe Trials | | | |
| CHI.1 | 53.9 | 307.5 | N.1 | 20.5 | 490.5 |
| CHI.2 | 159.7 | 220.7 | N.2 | 20.8 | 449.0 |
| CHI.3 | 80.5 | 306.9 | N.3 | 24.0 | 468.0 |
| CHI.4 | 32.7 | 394.0 | N.4 | 21.6 | 468.5 |
| CHI.5 | 73.0 | 297.1 | N.5 | 46.9 | 459.0 |
| CHI.6 | 127.0 | 338.1 | N.6 | 36.3 | 443.0 |
| CHI.7 | 88.9 | 283.7 | N.7 | 43.2 | 355.2 |
| CHI.8 | 100.0 | 312.8 | N.8 | 24.6 | 297.5 |
| CHI.9 | 70.0 | 286.1 | N.9 | 28.4 | 274.0 |
| CHI.10 | 34.5 | 371.9 | N.10 | 23.7 | 241.3 |
| CHI.11 | 49.3 | 367.2 | N.11 | 31.0 | 335.8 |
| CHI.12 | 116.1 | 176.1 | N.12 | 35.5 | 327.0 |
| CHI.13 | 103.7 | 222.0 | N.13 | 35.8 | 391.4 |
| Mean | 83.8 | 298.8 | | 30.3 | 384.6 |
| SD | 37.4 | 63.5 | | 9.0 | 84.3 |

Appendix F-7. Individual Subject Slope and Intercept Estimates for the Pattern Delayed Identity- Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| Positive Probe Trials | | | | | |
| CHI.1 | 117.3 | 288.5 | N.1 | 88.2 | 325.0 |
| CHI.2 | 175.7 | 243.1 | N.2 | 89.7 | 300.0 |
| CHI.3 | 125.4 | 339.3 | N.3 | 47.4 | 416.5 |
| CHI.4 | 198.6 | 166.0 | N.4 | 88.2 | 325.0 |
| CHI.5 | 96.2 | 394.3 | N.5 | 58.1 | 280.9 |
| CHI.6 | 135.1 | 365.1 | N.6 | 51.0 | 274.0 |
| CHI.7 | 49.0 | 446.3 | N.7 | 47.2 | 326.0 |
| CHI.8 | 52.8 | 521.2 | N.8 | 62.3 | 308.5 |
| CHI.9 | 75.7 | 327.7 | N.9 | 59.7 | 289.2 |
| CHI.10 | 146.9 | 191.3 | N.10 | 71.9 | 290.5 |
| CHI.11 | 133.7 | 307.8 | N.11 | 70.0 | 350.8 |
| CHI.12 | 69.1 | 299.8 | N.12 | 60.1 | 341.5 |
| CHI.13 | 68.8 | 362.4 | N.13 | 82.2 | 193.5 |
| Mean | 111.1 | 327.1 | | 67.4 | 309.3 |
| SD | 47.2 | 97.2 | | 15.6 | 51.1 |
| Negative Probe Trials | | | | | |
| CHI.1 | 125.6 | 251.5 | N.1 | 61.8 | 414.5 |
| CHI.2 | 98.5 | 386.4 | N.2 | 75.6 | 398.0 |
| CHI.3 | 96.2 | 338.5 | N.3 | 32.8 | 500.0 |
| CHI.4 | 72.7 | 425.4 | N.4 | 61.8 | 414.5 |
| CHI.5 | 22.1 | 455.0 | N.5 | 98.8 | 222.9 |
| CHI.6 | 193.2 | 321.8 | N.6 | 62.8 | 267.2 |
| CHI.7 | 105.0 | 303.6 | N.7 | 98.7 | 225.0 |
| CHI.8 | 146.3 | 351.6 | N.8 | 60.3 | 330.3 |
| CHI.9 | 23.7 | 443.7 | N.9 | 49.9 | 333.2 |
| CHI.10 | 58.9 | 387.1 | N.10 | 49.2 | 395.8 |
| CHI.11 | 135.0 | 347.0 | N.11 | 59.8 | 405.9 |
| CHI.12 | 74.4 | 330.9 | N.12 | 78.3 | 335.2 |
| CHI.13 | 123.9 | 316.4 | N.13 | 58.7 | 291.4 |
| Mean | 98.1 | 358.4 | | 65.3 | 348.8 |
| SD | 48.5 | 58.8 | | 18.7 | 82.3 |

Appendix F-8. Individual Subject Slope and Intercept Estimates for the Subtraction Identity-Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| | | Positive Probe Trials | | | |
| CHI.1 | 123.6 | 656.0 | N.1 | 178.5 | 470.0 |
| CHI.2 | -98.1 | 1828.1 | N.2 | 98.5 | 566.0 |
| CHI.3 | 132.4 | 746.7 | N.3 | 94.6 | 573.0 |
| CHI.4 | 346.8 | 103.7 | N.4 | 103.1 | 264.4 |
| CHI.5 | 209.3 | 443.6 | N.5 | 70.7 | 631.5 |
| CHI.6 | 173.6 | 769.5 | N.6 | 159.2 | 204.0 |
| CHI.7 | 97.9 | 690.6 | N.7 | 139.2 | 94.9 |
| CHI.8 | 98.1 | 818.1 | N.8 | 165.7 | 406.5 |
| CHI.9 | 204.9 | 340.8 | N.9 | 106.7 | 432.4 |
| CHI.10 | 358.8 | 4.6 | N.10 | 111.7 | 200.7 |
| CHI.11 | 293.3 | 999.4 | N.11 | 179.8 | 357.0 |
| CHI.12 | -49.6 | 1863.1 | N.12 | 47.1 | 509.5 |
| CHI.13 | -61.0 | 1878.1 | N.13 | 169.1 | 110.0 |
| Mean | 140.8 | 857.1 | | 124.9 | 370.8 |
| SD | 147.5 | 635.0 | | 43.3 | 181.1 |
| | | Negative Probe Trials | | | |
| CHI.1 | 263.6 | 738.8 | N.1 | 248.3 | 314.0 |
| CHI.2 | -37.4 | 2195.1 | N.2 | 161.4 | 420.5 |
| CHI.3 | 248.2 | 706.6 | N.3 | 205.4 | 349.0 |
| CHI.4 | 477.1 | 30.1 | N.4 | 135.1 | 234.1 |
| CHI.5 | 364.8 | 316.4 | N.5 | 176.1 | 485.7 |
| CHI.6 | 274.1 | 578.4 | N.6 | 211.7 | 87.4 |
| CHI.7 | 240.4 | 640.6 | N.7 | 123.2 | 149.6 |
| CHI.8 | 204.4 | 801.0 | N.8 | 180.7 | 342.1 |
| CHI.9 | 306.0 | 295.2 | N.9 | 110.5 | 378.0 |
| CHI.10 | 462.2 | 6.1 | N.10 | 123.8 | 158.7 |
| CHI.11 | 318.4 | 788.5 | N.11 | 195.5 | 283.2 |
| CHI.12 | 267.0 | 982.8 | N.12 | 102.0 | 410.8 |
| CHI.13 | 113.4 | 1507.0 | N.13 | 173.7 | 113.1 |
| Mean | 269.4 | 737.5 | | 165.2 | 286.6 |
| SD | 134.5 | 593.6 | | 44.2 | 128.1 |

Appendix F-9. Individual Subject Slope and Intercept Estimates for the Class Exemplar Categorization-Match Task.

| Closed Head-Injured Subjects | | | Control Subjects | | |
|---|---|---|---|---|---|
| Subject | Slope | Intercept | Subject | Slope | Intercept |
| | | Positive Probe Trials | | | |
| CHI.1 | 227.9 | 362.3 | N.1 | 152.2 | 779.0 |
| CHI.2 | 508.5 | 44.9 | N.2 | 110.3 | 721.0 |
| CHI.3 | 291.7 | 297.8 | N.3 | 41.5 | 625.5 |
| CHI.4 | 215.5 | 218.7 | N.4 | 77.42 | 362.0 |
| CHI.5 | 456.4 | 278.5 | N.5 | 84.2 | 406.8 |
| CHI.6 | 1438.5 | -1034.5 | N.6 | 8.0 | 420.3 |
| CHI.7 | 284.6 | 333.9 | N.7 | 26.7 | 505.5 |
| CHI.8 | 1082.5 | -1015.7 | N.8 | 9.1 | 496.6 |
| CHI.9 | 543.4 | 69.2 | N.9 | 32.8 | 434.1 |
| CHI.10 | 139.5 | 335.5 | N.10 | 44.9 | 621.6 |
| CHI.11 | 438.9 | 93.4 | N.11 | 38.9 | 339.2 |
| CHI.12 | 438.9 | 262.8 | N.12 | 22.0 | 370.6 |
| CHI.13 | 233.6 | 874.8 | N.13 | 70.9 | 362.0 |
| Mean | 484.6 | 86.3 | | 47.8 | 495.7 |
| SD | 373.5 | 534.2 | | 30.5 | 146.3 |
| | | Negative Probe Trials | | | |
| CHI.1 | 295.9 | 474.2 | N.1 | 159.6 | 642.0 |
| CHI.2 | 434.2 | 556.6 | N.2 | 128.8 | 697.0 |
| CHI.3 | 406.5 | 459.0 | N.3 | 30.2 | 646.0 |
| CHI.4 | 363.5 | 263.8 | N.4 | 65.9 | 392.8 |
| CHI.5 | 87.8 | 1418.8 | N.5 | 132.7 | 388.6 |
| CHI.6 | 329.8 | 1485.5 | N.6 | -9.6 | 471.7 |
| CHI.7 | 602.2 | 159.4 | N.7 | 38.3 | 471.8 |
| CHI.8 | 471.4 | 204.0 | N.8 | 13.0 | 486.1 |
| CHI.9 | 101.5 | 1359.4 | N.9 | 27.1 | 434.1 |
| CHI.10 | 360.6 | 185.2 | N.10 | 11.8 | 720.3 |
| CHI.11 | 473.9 | 524.8 | N.11 | -1.4 | 429.6 |
| CHI.12 | 504.4 | 185.2 | N.12 | 12.5 | 414.2 |
| CHI.13 | 248.7 | 1045.9 | N.13 | 71.3 | 381.8 |
| Mean | 360.0 | 640.1 | | 52.3 | 505.8 |
| SD | 150.2 | 505.0 | | 55.6 | 124.1 |

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