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The Cognitive Psychophysiology of Diffuse Damage:
Contingent Negative Variation (CNV) Evidence of
Over- and Underprocessing after Severe Closed Head Injury

by

© J. Braxton Suffield

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

Department of Psychology

Carleton University

Ottawa, Ontario

August 1, 1985

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Abstract

A common consequence of severe closed head injury (CHI) is a generalized slowing of decision making, as measured by reaction time (RT) tasks. Because behavioral measures alone may not elucidate the nature of the slowing, a physiological measure, the contingent negative variation (CNV), was employed to provide further insight.

Twenty-two survivors of severe head injury (M coma duration = 28 days, M PTA = 85 days) were selected from a larger group of 67 CHI admissions. All had made good recoveries or were moderately disabled. Eighteen passed neurosensory screening (far-field somatosensory and auditory evoked potentials, behavioral audiograms), and were subsequently tested in two Go/NoGo CNV paradigms 1 to 6 years after injury.

Fifteen of 18 patients had abnormal CNVs, whereas an equal proportion of controls had normal CNVs. Two types of aberrant CNVs were found. In 10 patients, the centroparietal E-wave of the CNV was very much attenuated just prior to a slow behavioral response. This suggests that these patients were inadequately preparing to respond. This underprocessing of information may help to explain the slowed RT, and may be related to the apathy and hypoarousal often seen after CHI. In 7 of 18 patients, an early frontocentral CNV O-wave was abnormally large after a warning stimulus indicated subsequent stimuli could be ignored. Thus, these patients devoted an inappropriate amount of time and energy to the processing of irrelevant information; they overprocessed the warning stimuli. This overvigilance might be one source of the fatigueability so often reported in this population. CNV changes were not related patients' demographic data, including severity of injury, age at injury, time since injury, or outcome.

These hypotheses seem to account for much of the slowing of RT after CHI. No control had both slow RTs and aberrant CNVs, whereas 93% of patients with slow RTs had aberrant CNVs. Moreover, signs of over- and underprocessing were largely independent; only 2 patients showed evidence of both types of anomaly. RT accurately identified those patients who had sustained head injuries, but did not readily suggest the nature of the behavioral slowing; under- and over-processing groups had nearly identical RTs.

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Organizational Note

The text of this dissertation consists of four chapters. The Figures, Figure Legends and Tables referred to within each chapter are placed at the end of the corresponding chapter. These materials are numbered in accordance with the chapter, e.g., Figure 2-3 is the third Figure in the second chapter. All references are presented at the end of the dissertation.

Chapter
Introduction

Epidemiology of Closed Head Injury (CHI)

Incidence

Approximately half of all deaths are due to accidental injury. Among young adults, trauma is the single greatest cause of death (Trunkey, 1983). The proportion of these deaths due to head injury is difficult to establish, because deaths are typically classified by the external cause (eg., traffic accident) rather than the nature of the injury, such as head injury (Annegers, Grabow, Kurland & Laws, 1980). However, Hay (1967) determined that about 40% of the nearly 11,000 accidental deaths in Canada in 1965 were due to head injuries. A very recent study in Winnipeg, Manitoba indicated that about half of head injury deaths are sustained in motor vehicle accidents (MVAs; Parkinson, Stephensen, & Phillips, 1985).

In spite of the fact that the number of passenger-miles has greatly increased since 1965, the total number of motor vehicle deaths in North America has remained roughly constant (Cooper, 1982a). While the compulsory use of seat belts, reduced speed limits and improved traffic safety have prevented or reduced the severity of many injuries, the reduction in the number of traffic deaths is also due to recent advances in neurosurgical life-saving measures (Levin, Benton & Grossman, 1982). However, many survivors are not unimpaired; for every trauma victim who dies, there are two persons permanently

disabled (Kalsbeek, McLaurin, Harris & Miller, 1980). After head injury, these permanent disabilities are more often cognitive and psychological than physical (Jennett & Bond, 1975; Ommaya & Gennarelli, 1976). Evidence suggests that even very mild head injury is associated with lasting cognitive deficits (Boll, 1982; Levin, Grossman & Kelly, 1977).

In addition to the Canadian surveys by Hay (1967) and Parkinson et al. (1985), the incidence of head injuries has been evaluated by several studies in the United States. The U.S. Bureau of the Census estimated that 9,759,000 head injuries occurred in 1977 alone (Cooper, 1982a). While most of these injuries were not serious enough to warrant admission to hospital, more than 2 million injuries involved skull fracture and/or intracranial injury. If this ratio is extrapolated to Canada, it would indicate some 200,000 cases of serious head injury per year.

To get a better understanding of the number of head injury survivors, the U.S. National Institute of Neurological and Communicative Disorders and Stroke (NINCDS) initiated the nationwide Head and Spinal Cord Injury (HSCI) Survey in 1974. The major findings of that study were reported by Kalsbeek et al. in 1980. Based on multistage sampling of discharge records within certain U.S. counties, there were approximately 422,000 people discharged from hospital with a diagnosis of intracranial injury in 1974. This corresponds to an estimated incidence of 200/100,000 population, or 1 in 500.

The HSCI figures are lower than the census figures for several reasons. The HSCI study excluded patients who were not admitted to hospital, either because the injury was considered too slight to

warrant admission, or because the person was dead on arrival at the hospital (Anderson, Kalsbeek & Hartwell, 1980). The omission of this latter group is important; Klauber, Barrett-Connor, Marshall and Bowers (1981) reported that immediate fatalities account for about 65% of deaths after head injury. In addition, the HSCI survey did not include skull fractures.

The NINCDS also sponsored the Health Interview Survey of 1975 (Caveness, 1977; Kraus, 1980). The study included incidents of trauma to the head that prompted the injured to seek medical attention and/or resulted in at least one day of reduced activity. The incidence of these accidents was high -- 600/100,000 -- perhaps because the definition of head injury was rather broad, including trauma to the skull and face.

Neither of the NINCDS surveys assessed the severity of head injury. Specific clinical criteria of head injury were used in a study conducted by Annegers et al. (1980). This study was restricted to the population of Olmstead County, Minnesota, and included only the more serious cases of head injury. All cases showed evidence of the "pressured brain involvement" common to the patients in the present study: loss of consciousness, neurologic signs of brain injury, skull fracture, and/or post-traumatic amnesia. In addition, the Annegers et al. (1980) survey included persons killed at the scene of the accident, when the death could be attributed to head injury. The incidence was very close to that reported in the HSCI survey: 274/100,000 for males, and 116/100,000 for females.

Another measure of the frequency of head injury is the number of existing cases receiving treatment for head injury during the period

of study (usually a year). This statistic includes survivors of previous head injury still being treated for sequelae (Kraus, 1980).

The HSCI results suggest that 926,000 head injuries hospitalized between 1970 and 1974 still showed sequelae during 1974. However, this is likely an underestimate, as patients injured prior to 1970 but still receiving treatment in 1974 were excluded. As Levin et al. (1982) point out, the number of people recovering from previous injuries is difficult to estimate without neuropsychological assessment. The HSCI survey assumed that a person who suffered a head injury was fully recovered if the person was simply alive 6 months after the accident (Anderson et al., 1980). Even so, based on a continental U.S. population of 210.7 million, this represents a prevalence of 439 head injuries per 100,000 population, or 1 injury among every 238 people. This rate jumps to 1 in 143 among 15-24 year olds.

These statistics do not provide a clear indication of the proportion of serious head injuries relative to the total number of head injuries. Klauber et al. (1981) determined that out of all head injuries, only about 30% are serious enough to require hospitalization (Bowers & Marshall, 1980). Bricolo, Turazzi and Ferriotti (1980) found that of all patients with acute traumatic coma, only 4% were in coma longer than two weeks. These patients represented 0.6% of all patients hospitalized for head injury.

Causes of Head Injury

It is clear from several sources that in industrialized countries, motor vehicle accidents (MVAs) are the single greatest

cause of head injury. MVAs account for about one-half of all accidental deaths, or about 21% of all deaths. Depending on the country studied, head injury accounts for between 50-75% of MVA deaths (Sano, 1965, cited in Cooper, 1982a).

The probability that a head injury was incurred in a MVA increases with the severity of the injury; 70% of coma-inducing head injuries are sustained in MVAs (Miller, Sweet, Narayan & Becker, 1978). This proportion is as high as 82% among 15-29 year olds (Marshall, Becker, Bowers, Cayard, Eisenberg, Gross et al., 1983). As described below, the coma induced in a MVA is likely to be due to severe primary diffuse brain damage, as about 79% of the brain injuries sustained in MVAs are closed head injuries, rather than penetrating wounds (Kalsbeek et al., 1980). Data from the U.S. National Safety Council and Australia (Ryan, 1967) suggests that the head is injured in 70% of trauma-inducing MVAs, and is more likely to result in a fatality than injury to any other part of the body (Cooper, 1982a).

There is some question as to the application of U.S. traffic statistics to the Canadian population, given recent seat belt legislation in parts of this country. However, in 1975, one year before the introduction of seat belt legislation, Canada had the highest automobile fatality rate in North America and Western Europe, and the number of fatalities per 100,000 passenger cars was nearly twice that of the U.S. (U.S. National Highway Safety Administration, 1977, cited in Cooper, 1982a). A recent report suggests that seat belt use is greatly affected by these laws; in the four provinces that required the use of restraints, 45% of drivers complied. In the

remaining provinces, the use of seat belts was less than 10% (Arora & Lawson, 1982). If compliance with seat belt laws is high, as many as half of all serious injuries to car occupants can be prevented (Aldman, 1970). Moreover, the percentage of head injuries will drop the most (Christian, 1976).

Who is Injured

Unfortunately, those at greatest risk for head injury are precisely those least likely to obey seat belt laws, speed limits, drunk-driving laws, or other traffic safety regulations. Those who do obey seat belt laws are least likely to have an accident in the first place. Klauber et al. (1981) have shown that head injury is most common in young adults under 30. In fact, while the incidence of head injury in the general population is about 1 in 500, the incidence among 15-24 year old males is 1 in 150 (Annegers et al., 1980). Between the ages of 10 and 30, head injuries are the leading cause of death, accounting for about 40% of all mortalities in this group. The rate of occurrence in males is twice that of females.

In the young adult population, many of these MVAs occur on the weekend, and a large proportion (up to 50%) involve a drinking driver. From epidemiological studies in Canada and in the United States, a relatively clear picture of the person most at risk for head injury emerges: he is a young unemployed male, separated, divorced, or single. He is driving under a suspended licence, at 2 a.m. on a Sunday morning. Both he and his female passenger are under the influence of drugs, alcohol, or both. In addition, he likely has a history of antisocial behavior and/or previous head injury (Annegers

et al., 1980; Fahy, Irving & Millack, 1967; Kalsbeek et al., 1980; Kerr, Kay and Lassman, 1971; Parkinson et al., 1985; Rosenthal & Muir, 1983).

Hospitalization

Although head injuries make up only about 1% of all hospital admissions, the time required for recuperation is longer than for other injuries. Of course, the length of stay in hospital is also related to the severity of injury. When all head injuries are considered, the average stay is about 5 days (Kalsbeek et al., 1980). When only serious (coma-inducing) head injuries are considered, the average length of hospitalization increases dramatically, and varies inversely with outcome (Giannotta, Weiner & Cerverha, (1982). For example, patients who are destined to good recoveries have an average stay of 30 days, while those who remain in a persistent vegetative state have an initial hospitalization of 112 days. These latter patients almost invariably succumb to their injuries (Pinn & Posner, 1980).

Neuropathology of Closed Head Injury (CHI)

Head injuries fall into two major categories: penetrating wounds, typically produced by projectiles such as bullets, and nonpenetrating or closed head injuries (CHIs). The discussion of mechanisms of head injury will be restricted to the latter type, since

most head injury victims (and all patients in this study) suffered CHIs.

Recent reviews (Gennarelli, 1982; Levin et al., 1982; Ommaya and Gennarelli, 1976) suggest that CHI is associated with both focal and diffuse patterns of neuropathology.

Focal Lesions

Intracranial mass lesions, including extradural, subdural and intracerebral hematomas, occur in about 40% of head injury admissions (Miller, Butterworth, Gudeman, Faulkner, Choi, Selhorst et al., 1981). Cerebral contusions are also prevalent, seen in about 40% of CT scans after CHI (Dublin, French & Rennick, 1977). While often the result of a blow to the head (impact injury), some of these injuries also occur in the absence of impact, through inertial loading.

If the head strikes or is struck by an object, the skull distorts as the energy passes through it and into the brain. The blow may not only fracture the skull, but may also cause the detachment of the dura from the inner table of the skull. Fortunately, skull fracture indicates brain damage only about half the time (Jamieson and Yelland, 1972). Thus, while brain injuries are often associated with skull fracture, the presence of a fracture does not necessarily imply intracranial damage.

Skull distortions due to impact can produce lesions far removed from the site of impact. These "contrecoup" effects result from the relative movement of the brain during impact (Gurdjian & Gurdjian, 1976). Regardless of the site of impact, contrecoup lesions occur most frequently on the undersurfaces of the frontal and temporal

lobes, where the cortex has been scoured by the bony extensions of the skull. Gennarelli, Abel, Adams & Graham (1979) have reported that the frontal lobes are more susceptible to contusions than the temporal lobes, suggesting that temporal contusions rarely occur without frontal pathology. Because of the smooth surface of the occiput, contrecoup contusions in that region are rare (Gurdjian & Gurdjian, 1976).

Importantly, most of these focal brain lesions can occur in the absence of skull fracture or even head impact, under conditions of inertial loading (Cooper, 1982b; T.A. Gennarelli, personal communication, June, 1984; Ommaya & Gennarelli, 1976). These so-called acceleration/ deceleration injuries are most common in traffic accidents in which the moving head hits a fixed object, or is restrained by the neck, inducing a rotational acceleration/ deceleration. Direct observation of the brain under conditions of pure inertial loading indicate that it literally swirls in its case, rubbing against the inside of the skull (Holbourn, 1943; Pudenz & Sheldon, 1946). Again, the most vulnerable regions are the inferior surfaces of the frontal and temporal lobes, which are held in place by the rough surfaces of the fronto-temporal fossae and the sphenoid wings.

Pressure Effects

In addition to causing local damage, space-occupying lesions can also set off secondary insults, which in turn cause diffuse bilateral lesions. Notable among these are pressure effects, including increased intracranial pressure (ICP).

Elevated ICP (> 20 mm Hg) occurs in about 75% of severe CHIs (Miller, Becker, Ward, Sullivan, Adams & Rosner, 1977), and is one of the leading cause of death after CHI (Marshall, Smith & Shapiro, 1979). Pressure effects occur because the skull, housing the brain, cerebrospinal fluid and the cerebral blood supply, is basically a closed container. Within limits, an increase in the volume of one of these three components can be accommodated by displacement of the other two. However, if the limits are exceeded, and ICP continues to rise, the consequences can be disastrous. The blood supply to the brain may be reduced, resulting in diffuse ischemic brain damage. Bakay and Glasauer (1980) reported that as many as half of all deaths after CHI are due to ischemic damage secondary to increased ICP. The enlarged brain may also herniate through available openings. Fortunately, advances in understanding the mechanisms of ICP have improved monitoring and treatment regimens.

The mechanisms of other systemic reactions to CHI are not yet known, and therefore more difficult to control. In about 1/3 of more serious head injuries, a massive swelling of the cerebral tissue occurs (Snoek, Jennett, Adams, Graham & Doyle, 1979; Waga, Tochio & Sakakura, 1979). Both focal and diffuse swelling effects may occur, either immediately after injury or minutes or hours post-trauma. Curiously, the swelling is not restricted to severe injuries, nor does the amount of swelling correlate well with the severity of the initial injury. In milder cases of diffuse injury, the swelling effect may be the most serious threat to survival (Gennarelli, 1982).

Shearing Injuries

With survival, a pattern of deficits has emerged which suggests primary and bilaterally diffuse damage to white matter. Current evidence suggests that it is these microscopic white matter lesions, induced by sudden acceleration and deceleration of the head and its contents, that represent the most significant source of brain damage in closed head injury (Adams, Graham, Murray & Scott, 1982; Adams, Mitchell, Graham, & Doyle, 1977; Gennarelli, 1982; Gennarelli, Thibault, Adams, Graham, Thompson & Marciniak, 1982; Strich, 1956, 1961). Moreover, it is the combination of focal lesions, superimposed on a background of diffuse bilateral damage, that largely determines the quality of life after severe CHI (Levin et al., 1982).

As described above, if the head is free to move on the neck during impact, it and its contents undergo an extremely rapid rotational acceleration/deceleration, actually shaking the brain. Holbourn (1943) hypothesized that under these conditions the relatively incompressible brain changes shape in response to the loading forces, producing a shearing effect. He further predicted that shear would be particularly severe between brain regions of high and low density, and in areas where the brain is held in place by anatomical features of the skull. Because white matter is weakest in the shearing mode, the result would be a diffuse, bilateral disruption of axon processes, relatively more severe in the temporal and frontal lobes. Empirical evidence from brain models as well as pathologic data from monkeys and humans has largely borne out these concepts.

Adams and his colleagues (Adams, Graham, Scott, Parker & Doyle, 1980) have recently described the time course of diffuse axonal injury

(DAI), which they argue is a distinct neuropathological entity.

During the acceleration/deceleration phase, there is immediate injury to white matter axons in both hemispheres and the brainstem. These lesions take the form of microscopic balls of axoplasm (retraction balls), oozing out of the torn fibers (Strich, 1956, 1961).

Importantly, these microscopic lesions are typically not evident in CT scans (Alexander, 1982).

Simultaneously, gross (macroscopic) lesions may occur in the brainstem (Adams et al., 1982). Also at this time hemorrhagic tears may occur in the corpus callosum, fornix, and periventricular regions (Gennarelli, 1982). Over several days the retraction balls disappear, their loss associated with an increase in microglial clusters.

Several weeks post-injury, the white matter bulk decreases, as long fiber tracts degenerate. These later changes can be visualized on CT scan as an enlargement and rounding of the corners of the lateral ventricles. Thus, DAI can be characterized by a triad of signs (Adams et al., 1982): microscopic evidence of diffuse axonal damage, focal callosal lesions, and lesions in the rostral brainstem.

Importantly, these authors note that the etiology of DAI is not related to impact, but to acceleration/deceleration. Fully 71% of the 45 patients with DAI who came to autopsy had no evidence of skull fracture. These authors also suggested that intracranial mass lesions are infrequent in DAI. Compared to a group of 132 non-missile head injuries, the DAI group had fewer contusions and intracerebral hematomas.

Similar results have been reported by Gennarelli and his colleagues, studying acceleration/deceleration injuries in non-human

primates. Among 45 head-injured monkeys, there were no skull fractures, no hematomas, no infarctions, and no hypoxia. The contusions which did appear were small. Interestingly, Ommaya and Gennarelli (1976) found that when acceleration was restricted to translational movement, loss of consciousness did not occur, and only focal lesions were found. After angular accelerations (in which the head was free to move on the neck), these same accelerations produced extensive diffuse damage, and only few focal lesions.

In an expansion of earlier work, Gennarelli (1982) suggested that DAI represents a continuum of injury severity, increasing with greater angular acceleration. In a description of four levels of cerebral concussion, he reports that in general, the amount of functional disruption is always greater than the amount of anatomical disruption. At very low levels of acceleration, no injury is incurred. Mild concussion results at higher accelerations, causing transient disturbance of neurological function (confusion and disorientation, with or without amnesia), but no loss of consciousness. Classical cerebral concussion, another form of physiological disruption without permanent anatomical damage, occurs at higher acceleration. The hallmarks of this post-traumatic state include transient loss of consciousness and temporary, reversible neurological deficits. It represents diffuse hemisphereic disconnection from the brainstem reticular activating system.

Anatomical damage occurs as the level of acceleration increases further; in the category of concussion called diffuse injury, physiological dysfunction is pronounced, invariably involving loss of consciousness for days or weeks. This level of injury implies mild,

diffuse anatomical damage to longer, weaker fiber tracts, and proportionally greater neurological and psychological impairments in the short-term. Mild-to-moderate memory and motor problems will persist long after the injury, as will personality changes.

Gennarelli (1982) calls the most severe form of diffuse injury the diffuse white matter shearing injury. It is associated with the mechanical disruption of many axons in both hemispheres and the brainstem. Approximately 90% of those with this severity of injury either succumb to their injuries, or remain in a persistent vegetative state. The few patients who do recover suffer severe disabilities in cognitive function.

Acute Neurobehavioral Consequences of CHI

Mechanisms of Coma

The most obvious immediate response to severe CHI is loss of consciousness, the mechanisms of which are still largely unknown (Plum & Posner, 1980). While several systems are likely involved, traumatic unconsciousness suggests at least widespread dysfunction of the cerebral hemispheres, brainstem, or both. However, despite several physiological and pathological studies, it is difficult to determine whether the brainstem is affected relatively more or less than higher centers.

Foltz and Schmidt (1956) found that the activity of units in the reticular formation of experimental animals was transiently interrupted immediately after concussion. Ommaya and Gennarelli

(1976) concussed squirrel monkeys while recording somatosensory evoked responses from the dura above the hemispheres. Because the onset and offset of paralytic unconsciousness coincided precisely with the integrity of a electrical potential recorded from the rostral brainstem, they concluded that the structures of the mesencephalon were integral to the maintenance of consciousness.

It must be pointed out that these recordings were made in severely concussed animals. Ommaya and Gennarelli (1976) stressed that the brainstem and mesencephalic core are relatively resistant to the primary lesion of trauma such as shearing and contusion; the cerebral hemispheres suffer relatively more at a given input force. The authors stated that the acceleration/ deceleration effects of head trauma decrease in magnitude from the surface to the center of the brain, with the brainstem suffering last and least. Thus, paralytic coma is not produced until the shear strain "is large enough to reach the well-protected mesencephalic part of the brainstem and thus complete the disconnection of the alerting system of the brain" (Ommaya & Gennarelli, 1976, p. 52). Mitchell and Hume-Adams (1973) surveyed the incidence of primary brainstem lesions in patients who did not survive head injury, and concluded that brainstem lesions did not occur without severe damage elsewhere.

Coma Scales

The depth and duration of coma are considered reliable prognostic signs (Levin et al., 1982). The most widely used standardized measure of coma is the Glasgow Coma Scale (GCS), developed by Teasdale and Jennett (1974). This scale (Table 1-1) rates the patient's best motor

response, the minimum stimulus that produces eye opening, and the best verbal response.

----- Table 1-1 about here -----

By summing the scores from the three categories, possible scores range from 3 (no response in any category) to 15 (fully conscious and oriented). Levin et al. (1982) used a summed score to operationally define coma as a score of 8 or less after nonsurgical resuscitation. Behaviorally, this usually represents an inability to open the eyes, utter recognizable words, or follow simple commands. Because early neurological status is so variable, many users of the scale require that a score of 8 or less be maintained for 6 or more hours before coma is defined (Jennett, Teasdale, Braakman, Mindrehoud, Heiden & Kurza, 1979). The probability of survival decreases with GCS scores below 7 (Marshall et al., 1983).

The concise nature of the scale and its inter-rater reliability make it practical to determine the GCS repeatedly. Teasdale, Jennett, Murray and Murray (1983) found that repeated testing provided better prognostic information than scores obtained at admission. On the other hand, Jagger, Jane and Rimel (1983) and Gildenberg (1981) have criticized the scale on the grounds that it poorly differentiates between various levels of severe head injury. This is because people who are in coma typically have no eye or verbal response, leaving only the 4 degrees of freedom in the motor response. When barbituate therapy is used to lower ICP, it also immobilizes the patient, rendering even the motor response useless.

Use of the GCS is still far from universal. None of the patients in the current study were rated on the Glasgow Coma Scale while in the acute state. However, the score can be determined retrospectively from medical notes made at admission and during the patients' clinical course. Moreover, this study is more concerned with patients' outcome long after injury. Thus, in addition to the retrospectively scored GCS, two outcome scales were used, described later in this chapter.

Coma Duration

Along with depth of coma, the duration of coma has long been thought to be predictive of eventual outcome. This is because recovery after nervous system injury is often considered a race against time; the faster recovery begins, the better the prognosis. With the advent of the GCS, it has been possible to more accurately determine when a patient emerges from coma, and therefore test this assumption.

The data are, in fact, contradictory. With relatively short coma durations, the relation between coma and cognitive outcome is not reliable. Brooks and Aughton (1979) could find no differences in the cognitive performances of patients who had been in coma for 1, 2 to 3, or 4 or more days. Using similar group definitions, Alexandre, Colombo, Neritampi and Benedetti (1983) found the GCS and the neurological syndrome involved were much better predictors of eventual outcome than coma duration.

Longer coma durations are more reliable, if discouraging, predictors. Levin, Grossman, Rose and Teasdale (1979a) found that patients who went on to make good recoveries had significantly shorter

comas (median = 1 day) than those who were left with moderate or severe disabilities (median comas of 13 and 17 days, respectively). However, there was a wide range of coma duration within each outcome group, suggesting that coma duration is not a certain predictor of outcome. The relationship between coma duration and GCS at admission was also vague; Levin et al. (1979a) found GCS on day 2 or day 3 to be more highly correlated with outcome.

Among survivors with good recoveries, Lezak (1979) found that patients who had been in coma for more than 2 weeks were consistently more impaired on tests of auditory verbal learning than patients with shorter comas. However, she too noted large variability both in performance and coma measures. Moreover, she did not specify how she defined coma, or determined when it was terminated.

This is an important consideration when the period of unconsciousness extends beyond two weeks; Bricolo et al. (1980) established that coma longer than two weeks is not homogeneous, but consists of several states. Relatively few of their patients stayed in coma for more than one month, but either died (usually within 2 - 3 months) or entered into a vegetative state of wakefulness without awareness ("coma vigil"). If significant neurological improvement did not occur within 3 months, it was unlikely to occur at all; while 52% of patients began to execute verbal commands in the first 3 months, only 14% of the remaining patients began to execute commands subsequently. At the one year follow-up, one-third of the patients had died, one-third remained vegetative or totally dependent, and one-third had made satisfactory recoveries.

Bricolo et al. (1980) did not find early neurological status to be particularly useful in predicting length of coma. In fact, most of their patients had initially shown coma of less than extreme severity, suggesting that the coma was somehow self-sustaining, perhaps by extracranial injuries. This might explain why death was not correlated with any one initial injury severity.

In summary, the duration of coma is not as predictive as initial injury severity when coma is less than two weeks. With longer durations, the mechanisms which initially produced the coma seem to give way to events which perpetuate it, lowering the predictability of outcome by any means. In general, however, the longer the patient remains without improvement, the less marked eventual improvement will be.

Post-Traumatic Amnesia

As survivors of severe head injury emerge from coma, they enter a period of variable duration in which they are confused, disoriented, and cannot maintain continuous memory; this is the period of post-traumatic amnesia (PTA). In addition, there is often a loss of memory for events just prior to the injury (retrograde amnesia or RA). Perhaps best described by Russell (1971), PTA is the most consistent clinical finding after closed head injury (Levin et al., 1982).

Like duration and depth of coma, the length of time before continuous memory is reestablished has been found to be a more or less reliable indicator of the severity of brain damage and patient prognosis (Levin et al., 1982). Unfortunately, like coma, PTA is not an "all or none" phenomenon. Its measurement is complicated by

so-called "islands of memory" in which the patient appears to emerge from his amnesia and disorientation, only to slip back within hours or days (Russell & Nathan, 1946). There is no widely accepted technique for assessing the duration of PTA, leading to variability between reports in the literature.

When first described by Russell in 1932, PTA referred to the time between injury and the time when the patient remembered "waking up." Russell and Nathan (1946) changed this criterion to terminate when the patient had continuous memory for ongoing events. They felt that this indexed duration of impaired consciousness, rather than duration of unconsciousness.

In their review of PTA research, Schacter and Crovitz (1977) used a similar criterion, but noted that some authors differentiated between post-traumatic conditions. Although some (Moore & Ruesch, 1944; Sisler & Penner, 1975) have considered disorientation, retrograde amnesia and anterograde amnesia to be separate aspects of PTA, the term traditionally refers to the time between injury and the return of consistent orientation and continuous memory (Schacter & Crovitz, 1977). Russell (1971) pointed out the return of these functions is typically coincident. The end of PTA also corresponds with the disappearance of confusion (Jennett, 1976). Even so, this transition is a gradual process.

Perhaps because of this slow resolution, few quantitative tests of PTA exist. Benton, Van Allen and Fogel (1964) used brief quantitative tests of temporal and personal orientation to differentiate brain-damaged from other hospitalized patients. This test was modified by Levin, O'Donnell and Grossman (1979b) to include

evaluation of memory for events around the time of trauma. The resulting Galveston Orientation and Amnesic Test, or GOAT, is designed for repeated administration. As such, it can provide a continuous recovery curve as patients emerge from their PTA, much as the GCS provides a measure of emergence from coma.

Assessment of PTA can be used retrospectively to estimate injury severity. In a 1961 editorial, The Lancet concluded that PTA was the best available measure of injury severity, a conclusion also reached by Fahy et al. (1967). The association between PTA and injury severity has since been confirmed in several studies, both in military (eg. Russell, 1971) and civilian (eg. Jennett, 1976; Levin et al., 1982) populations. Importantly, this relationship has continued to hold as measures of both injury severity and PTA have become more sophisticated.

PTA duration can also be used to predict the eventual quality of recovery from head injury. Russell and Smith (1961) found significant correlations between PTA duration and residual memory, computational and motor deficits, as well as aphasia and anosmia. Importantly, persistent memory deficits were more pronounced in older patients (> 30 years). Lishman (1973) found that PTAs of less than 24 hours were associated with complete cognitive recovery, while PTAs greater than 24 hours reflected varying degrees of cognitive loss. Although return to employment may not be a reliable measure (Jennett & Bond, 1975), Lishman's review indicated that patients with PTAs greater than one week were unable to return to work for a year or more.

These findings were confirmed by Jennett (1976), who found that as duration of PTA increased beyond 1 week, the proportion of patients

with moderate or severe disability increased 3-fold. Jennett, Snoek, Bond and Brooks (1981) determined that patients with PTAs of less than 4 weeks were virtually certain to become independent in activities of daily living (ADL), although perhaps cognitively disabled. A similar association was also found by Levin et al. (1979b) using the GOAT. They determined that patients with PTAs of less than two weeks made good recoveries, while longer PTAs suggested a poorer prognosis.

Evoked Potentials

Few measures other than the coma scale are useful in determining the functional integrity of the CNS in comatose patients. While some of the neurological examination can be performed on a comatose patient, the clinician's inability to communicate with the patient severely limits the amount of information obtained (Greenberg, Newlon & Becker, 1982). More elaborate diagnostic techniques, such as the CT scan, reflect the anatomical condition of the brain, but provide little information as to its functional integrity. Imaging techniques which do provide this information (eg., PET scans) are being developed, but the cost and time involved are prohibitive. Measures of ongoing brain electrical activity, such as the EEG, held early promise, but have not proved useful in comatose patients (Bricolo, Turazzi & Feriotti, 1979; Teasdale & Mendelow, 1984).

It has been known for some time that when the EEG is averaged in synchrony with sensory stimulation, the resulting "evoked potentials" provide a measure of brain function within the sensory pathways evaluated. Recently, Greenberg and colleagues (Greenberg, Becker,

Miller & Mayer, 1977a; Greenberg & Ducker, 1982; Greenberg, Mayer, Becker & Miller, 1977b; Greenberg et al., 1982) found that they could assess brain function in comatose patients by recording potentials evoked by auditory, visual and somatosensory stimulation. These multimodality evoked potentials (MEPs) were prognostic of outcome 6 months later. Subsequent analysis has revealed that auditory and visual EPs were largely redundant; much of the predictive information was available in somatosensory EPs (SEPs) alone (Pfurtscheller, Schwarz & Gravenstein, 1985). Greenberg et al. (1982) found that SEP data were the most reliable single predictor of outcome, producing fewer incorrect predictions than information from CT scan, ICP, Glasgow coma scale, age, motor posturing, or pupillary response. When SEP information was combined with clinical data (Glasgow Coma Scale, pupillary response, presence of mass lesions), predictions had an accuracy of 89%, with 64% of the predictions made above the 90% confidence level. At least part of the utility of the SEP is due to the extent of the nervous system evaluated in this modality. In contrast to the auditory response, which is limited to peripheral auditory nerve and brainstem structures, and the visual responses, which are regarded as cortical, the somatosensory evoked potential contains responses from the peripheral nervous system, several brainstem structures, and both primary and secondary cortical centers.

While some information is lost when only EPs from the somatosensory modality are used, this modality offers distinct advantages over the visual and auditory responses in comatose patients. By definition, comatose patients have their eyes closed; this fact requires that the visual stimulus used to elicit the

response be a bright flash. However, the normal response to this stimulus is highly variable, probably because of individual differences in the cortical topography of primary and associative visual cortex (Picton, 1979; Regan & Milner, 1978).

The clinical utility of brainstem auditory evoked potentials (BAEPs) is somewhat limited by the relatively low correlation between this response and clinical outcome (Chiappa & Ropper, 1982). Goldie, Chiappa, Young and Brooks (1981) found that patients with normal BAEPs had approximately equal probabilities of poor outcome (death or persistent vegetative state) and some functional recovery. Rappaport, Hopkins, Hall and Belleza (1981b) found that BAEPs correlated least with disability, often remaining intact in spite of obvious cerebral deficits. These findings are in accord with the concept that brainstem structures are resistant to damage during CHI. On the other hand, because these responses are so robust, the presence of an abnormal BAEP is a reliable, if discouraging, prognostic sign. For example, Goldie et al. (1981) found the BAEP useful in delineating brain death. Similarly, Tsubokawa, Nishimoto, Yamamoto, Kitamura, Katayama and Moriyasu (1980) found BAEP to be a more useful indicator of brainstem damage than CT scan or neurological findings. Karnaze, Marshall, McCarthy, Klauber & Bickford (1982) also found the BAEP useful, successfully predicting outcome in 88% of comatose patients.

Long-Term Neurobehavioral Consequences of CHI

Outcome Scales

Before describing the specific deficits common after severe injury, a word is appropriate on how long-term recovery is assessed. Measuring outcome after brain damage has been a neglected area, at least compared to the emphasis on measuring progress in the acute state. However, as Jennett (1984) has eloquently expressed, it is this long-term outcome which is perhaps most important to the patient, the patient's family, and society.

The standard against which outcome is measured depends greatly on the observer. Members of acute care teams may regard survival from deep coma as "remarkable," in spite of significant residual disabilities. On the other hand, the patient will be largely oblivious to this "recovery" because of coma and PTA. On the basis of his premorbid state, he may well judge himself as significantly disabled. The patient's family falls somewhere between these points of view. Knowing how close the patient came to death, they may at first consider residual deficits a small price for survival. However, as they come to realize that these disabilities, including significant personality changes, will last the lifetime of the (typically young) patient, they may come to share his attitude, and may even exaggerate positive pre-trauma attributes.

To circumvent the subjective nature of this exercise, Jennett and Bond (1975) developed the Glasgow Outcome Scale, a relatively objective method of categorizing recovery from acute brain injury. They arrived at four operationally defined outcome categories:

vegetative state, severe disability, moderate disability, and good recovery. Jennett et al. (1981) determined that 90% of all patients reached their final outcome level of disability within 6 months of injury. Only 5% ($n = 4$) of 82 patients with severe head injury improved sufficiently after 1 year to reach the next highest outcome category. These authors proposed that those wishing a more finely graded scale could subdivide the Good Recovery, Moderate Disability and Severe Disability categories into "better" and "worse" levels. However, the authors offered no operational definitions for these rather vague descriptors.

Recently, Rappaport and coworkers (Rappaport, Hall, Hopkins, Belleza & Cope, 1982) developed a more finely tuned scale to be used in a head injury rehabilitation center. Their Disability Rating Scale consists of 8 items in four categories.

On the Rappaport scale, arousal and awareness are graded on an "inverted" Glasgow Coma Scale; patients are given lower scores as they improve. The patient's cognitive ability to take care of feeding, toileting and grooming needs, independent of confounding motor deficits is also rated. Residual motor deficits are more directly assessed in a third category, which rates the patient's dependence on others for activities of daily living (ADL). Finally, the patient's "psychosocial adaptability," as reflected in "employability," is assessed. The scores from each of the 8 categories are added to yield a total, which places an individual in one of 10 disability categories.

Only two studies have sought to determine the relationship between the Glasgow Outcome Scale and the Rappaport scale, and they

may have been subject to bias. Rappaport and coworkers (Hall, Cope, & Rappaport, 1985; Rappaport et al., 1982) reported that their scale was a more sensitive index of rehabilitation progress than the more widely used GOS. This finding is not surprising, given the finer gradations of the Rappaport scale. However, the scale does have high interrater reliability, and has been shown to covary with the neurophysiological status of the patient, as measured by sensory evoked potentials (Rappaport, Hall, Hopkins & Belleze, 1981a; Rappaport et al., 1981b). One of the aims of the present study was a further evaluation of patients' outcome on both outcome scales.

Neurobehavioral Effects

As coma, PTA and other acute deficits subside, more extensive examination of neurological and mental status can be made. Discrete deficits are generally due to focal lesions such as coup and contrecoup injuries and hematomas. Common among these are problems with language, primary motor and sensory loss, and perceptual difficulties. One of the most common complaint after CHI is the memory impairment usually attributed to contusions of the anterior temporal lobes. The traumatic amnesia which results has been extensively reviewed by Brooks (1972, 1974, 1975), Brooks and Aughton (1979), Hannay, Levin and Grossman (1979), Russell (1932), Russell and Smith (1961), Schacter and Crovitz (1977), and Smith, 1974. In addition, personality changes, often leading to profound psychosocial difficulties, are a common consequence of frontal lesions. The hallmarks of the frontal lobe syndrome include losses of self-control, foresight, creativity and spontaneity. Behaviorally, these deficits

surface as increased irritability, selfishness, restlessness, and a general lack of concern for others. The impact of the character changes on the patient and family has been reviewed by several workers, including Boll (1982), Bond, 1984), Brooks (1984b), Brooks and McKinlay (1983), Lezak (1978), McKinlay, Brooks, Bond, Martinage and Marshall (1981), Oddy (1984), and Thomsen (1974).

Aside from the deficits brought on by focal lesions, the head injured patient is at great risk of diffuse damage. After even mild head injury, a complex of somatic and cognitive symptoms arises with such regularity that it is classified in the International Classification of Diseases (ICD-9; World Health Organization, 1978) as the Post-Concussion Syndrome, or PCS. It is described in DSM-III (American Psychiatric Association, 1980) as

States occurring after generalized contusions of the brain, in which the symptom picture may resemble that of the frontal lobe syndrome, or that of any of the neurotic disorders (eg. hysteria, hypochondriasis, phobic state), but in which in addition, headache, giddiness, fatigue, insomnia and a subjective feeling of impaired intellectual ability are usually prominent. Mood may fluctuate, and quite ordinary stress may produce exaggerated fear and apprehension. There may be marked intolerance of mental and physical exertion, undue sensitivity to noise, and hypochondriacal preoccupation. ...This syndrome is particularly associated with the closed type of head injury when signs of localized brain damage are slight or absent.

The relationship between prevalence of PCS and injury severity is not yet established. Some symptoms (eg. dizziness) appear more commonly after longer (> 12 hr.) PTA (Friedman, Brenner & Denny-Brown, 1945), while other symptoms (eg. headache, fatigue) show no clear relationship to injury severity (Brenner, Friedman, Merritt & Denny-Brown, 1944). Miller (1961) maintained that an inverse relationship existed between PCS and injury severity. However, this

inverse relationship may be artifactual; several authors have described a profound lack of insight in patients with more severe head injuries (eg. Brooks, 1984a; Lezak, 1983). These patients frequently deny or dismiss their (often significant) disabilities.

Information Processing After CHI

Short-Term Measures

PASAT. The measurement of short-term intellectual impairment is confounded by difficulties in getting information into and out of semi-conscious or disoriented patients. In large part, "higher-order" mental skills are secondary to attention and concentration abilities (Boll, 1982). To assess the extent to which head injured patients could attend to and process information, Gronwall (1972; cited in Gronwall & Wrightson, 1974) developed the Paced Auditory Serial Addition Test (PASAT).

The PASAT consists of a tape-recorded series of digits. The subject is asked to add each pair of numbers and respond with the sum before the next number is presented. Among normals, performance drops as the rate of presentation increases. Gronwall found that mildly concussed patients ($PTA < 1$ hr) initially performed poorly, but attained control levels by follow-up four weeks after discharge. Nearly all achieved normal performance within 35 days of injury. In contrast, later research with the PASAT showed that more severely concussed patients ($1 \text{ hr} < PTA < 8 \text{ days}$) were still well below

control performance 4 weeks after discharge (Gronwall & Wrightson, 1981).

Because the test requires the patient to process auditory information efficiently, hold an item in short-term memory for addition, and maintain attention and concentration, all at an imposed pace, Levin et al. (1982) referred to the PASAT as a "cognitive stress test." More simply, Gronwall and Wrightson (1981) describe the PASAT as a sensitive measure of information processing efficiency. PASAT performance correlates highly with fitness to work, especially the ability to return to occupations requiring sustained attention and rapid decisions. It has the further advantage of not being affected by premorbid academic achievement (Gronwall, 1977). Unfortunately, the PASAT is a difficult, somewhat tedious test, and can be rather unreliable (MacFlynn, Montgomery, Fenton & Rutherford, 1984). Also, because performance on the PASAT is affected by so many different psychological processes, its usefulness in determining precise effects of CHI is questionable.

Long-term Measures

Intelligence tests. On standardized intelligence tests such as the WAIS and WAIS-R, initial impairment tends to increase with increasing injury severity, whether severity is measured by time in coma (Klove & Cleeland, 1972) or PTA (Norrman & Svahn, 1961; Roberts, 1980). Long-term improvement from CHI is often associated with a moderate or good return of verbal IQ, in spite of the severity of injury. Performance IQ frequently also recovers to the same extent, but typically requires a longer time. Performance on timed motor

tasks is often especially slow to recover (Brown, 1975; Mandleberg & Brooks, 1975). Of performance tasks, problem-solving skills recovered more slowly than more basic skills (Dikman, Reitan, & Temkin, 1983; Mandleberg & Brooks, 1975). It is not clear why head injury patients find performance items so difficult, though the deficit has been considered symptomatic of diffuse injury for years. Both Conkey (1938) and Ruesch (1944) referred to problems with speeded performance and difficulty in maintaining a sustained effort over time. More recently, Dikman and colleagues (1983) determined that high-level functions such as reasoning, concept formation, flexibility of thought, and psychomotor problem solving speed were particularly vulnerable to CHI, and somewhat slower to return to estimated premorbid levels than more verbal skills. These formal test results are often confirmed by patients' complaints of "mental slowing."

Reaction Time after CHI. These data have been interpreted as evidence of a generalized slowing of head-injured patients' cognitive processes, especially those involved in the prompt and accurate use of information. Both simple and choice reaction time paradigms have been employed to isolate the nature of this slowed performance.

Interpretation of early studies is hampered by the poor methodology employed. For example, control subjects used by Ruesch (1944) were nearly 10 years younger than patients, while the mildly concussed patients tested by Dencker and Lofving (1958) were evaluated 10 years after injury.

Norrmann and Svahn (1961) exercised somewhat better experimental control, selecting patients who had suffered very severe concussions,

with loss of consciousness for over a week. Tested more than 2 years after injury, patients' performance on simple visual reaction time tasks did not differ from that of normal controls or non-injured neurotics. However, when Norrman and Svahn required subjects to choose from 3 response buttons in a choice reaction time (CRT) task, head injured patients were significantly slower than either control group. Thus, the key to the slowed processing in the head injury patients seemed related to choice behaviors, or decision making. Subsequent research has focused on differences between simple and choice reactions.

Miller (1970) not only indicated that head injured subjects were worse on choice- than simple- RT, but also that as the number of choices in the CRT task increased, their performance got worse. Analyzing his results in terms of information theory, Miller determined that as the amount of information to be processed increased, the greater the difference between head injured and control subjects. Extrapolating to "zero information" (ie., only response time), Miller concluded that the patients' slow RT could not be attributed to motor or sensory deficits. Rather, "the most parsimonious explanation must be that the effect of head injury must be to slow down the decision making and information processing abilities of the subject" (p. 126).

Gronwall and Sampson (1974) replicated Miller's findings among less severely injured patients. In their paradigm stimulus and response were incompatible; subjects had to respond to stimuli numbered from left to right by pressing response buttons numbered from right to left. As the number of stimulus/response pairs increased,

so did the difference between controls and patients. Their findings suggest that effects of mild head injuries differ only quantitatively from those due to more severe head trauma.

The most recently reported series of RT experiments among the adult head injured are those of van Zomeren (1981). Testing patients who had incurred mild, moderate or severe closed head injuries 3 - 6 months previously, van Zomeren confirmed previous findings that as the complexity of a choice reaction time task increased, patients' performance decreased. Moreover, the performance decrement was correlated to initial injury severity, as indexed by coma duration. Van Zomeren showed that the slope of the information processing speed function dropped with increasing time since injury, suggesting a steady improvement in these skills for at least 2 years after the injury.

Thus, slow responses in the head-injured population may be due to several factors. Van Zomeren suggested several mechanisms, ranging from delayed arousal (affecting early stages of stimulus evaluation) to slow motor movement (affecting response production). He also hypothesized an overly conservative response bias among patients, who tended to "double-check" before responding.

However, a number of psychologists have suggested that the use of the mean RT alone to investigate these hypotheses is overly simplistic. Reaction times can vary for several different reasons, only one of which is "stimulus evaluation time" (Biederman & Stacy, 1974; Pachella, Smith & Stanovich, 1978; Theios, 1975).

In an effort to determine whether slowed RT was due to slow stimulus evaluation or slow response production, van Zomeren devised a

task in which both "decision time" (DT; from presentation of the stimulus until the subject lifted his finger from the home key) and "movement time" (between release of the home key and contact with the target button) were recorded.

Compared to normal controls, very severely concussed patients had slightly longer movement times, and significantly longer decision times. Moreover, patients' decision times increased significantly with more complex tasks.

When an irrelevant distracting stimulus was presented along with the target stimulus, it significantly delayed the DT component among both patients and controls. However, the distractor disproportionately affected patients. In addition, patients also had slower movement times. Thus, goal-directed movements were significantly slower in patients than in controls, despite absence of clinical motor deficits. Consequently, van Zomeren (1981) concluded that head injury affected both decision and movement components of RT.

It seems, therefore, that isolated behavioral measures such as RT, cannot conclusively distinguish between deficits in stimulus evaluation and those affecting response production, at least without the use of elaborate experimental designs such as those suggested by Link (1982). Unfortunately, in addition to being controversial, such sophisticated paradigms typically require several hundreds (or thousands) of trials, hardly a practical choice in view of the known fatiguability of CHI patients. Given the available evidence, then, it is not yet clear whether head injured patients "think" slowly, move slowly, or both.

Recently, Campbell and others (Campbell, Houle, Lorrain, Deacon-Elliott & Proulx, in press) used a combination of physiological (event-related brain potentials) and behavioral measures (RT) in an attempt to disassociate the stimulus evaluation/ response production confound. While RT is influenced by both stimulus evaluation and response production, a late positive waveform, P3, appears to be primarily influenced by the former (Kutas, McCarthy & Donchin, 1977; McCarthy & Donchin, 1980). The studies of Campbell et al. indicated that CHI patients' RTs were approximately 150 ms slower than controls. However, P3 latency was delayed by only 50 - 75 ms, indicating that while stimulus evaluation processes are slowed, response production processes also play a significant role in the overall delay of RT after CHI. One of the purposes of the present study is to attempt to account for the slowing of stimulus evaluation processes. Van Zomeren (1981) has suggested that the slowing could be due to a failure to develop adequate preparatory set prior to the onset of the target stimulus. A physiological measure, the contingent negative variation, or CNV, provides a means of monitoring the brain's activity in preparation for action.

Neurophysiological Measures of Information Processing

Contingent Negative Variation

In a forewarned reaction time task, a slow negative shift in the baseline or DC level of the EEG can be observed. As mentioned, this shift is called the Contingent Negative Variation or CNV (Walter,

Cooper, Aldridge, McCallum & Winter, 1964). It was called "contingent" because the broad negative wave seemed to depend on the association of 2 stimuli: a warning stimulus (WS or S1) and a second, imperative stimulus (IS or S2) to which the subject might have to respond. In addition, Walter et al. (1964) were likely influenced by Caton (1875), who recorded the first brain potentials: "when any part of the grey matter is in a state of functional activity, its electric current usually exhibits contingent variation" (p. 278).

Because the CNV is not always clear in the raw EEG, signal averaging is used to improve the signal-to-noise ratio. The theory of signal averaging assumes that the response (the "signal") is constant in the random, ongoing background "noise" of the EEG. If on any given trial, a particular electrical potential might be randomly positive or randomly negative, over a series of trials the average of these potentials should be close to zero. On the other hand, over a series of trials, the average of a constant potential is always the same. Thus, given enough trials, the background "noise" should average out, leaving only the constant signal. Since the CNV is a relatively large signal (10 to 20 μV compared to less than 1 μV for BAEPs), relatively few trials are required to average out the background noise.

One of the major methodological considerations with use of the signal averaging technique is a concern for artifact (Hillyard & Galambos, 1970; Picton & Hillyard, 1972; Tecce, 1972). Frequently, non-cerebral artifact from sources such as the muscles, ocular movement, blinking and electro-dermal responses (EDRs) contaminate the EEG. To avoid confounding, artifact must be removed. Proper electrode technique and instructions to subjects can often reduce many

sources. However, this is often not enough, particularly with patient populations. A simple means of avoiding non-cerebral contamination is to program the computer which performs the averaging of the EEG signals to reject trials in which the incoming signals exceed typical EEG amplitude.

Psychological states associated with the CNV. Because of a long association between negativity at the scalp and cortical activity, Walter et al. (1964) suggested that the CNV was a sign of "cortical priming" or preparation to respond to the impending S2. Later work by Walter suggested that the development and size of the CNV was also a function of the probability of the occurrence of S2, and he (1965) began calling the CNV the "expectancy-" or "E-wave." Although Walter eventually (1973) came to deplore the use of ill-defined psychological concepts in describing the CNV, in 1966 he cited several additional factors which played on the development of the potential, including readiness, motivation, attention, and expectancy. The termination of the potential was found to hinge on subjects' recognition, decision, action and consummation (Walter, 1966). Irwin and colleagues (Irwin, Knott, McAdam & Rebert, 1966; Rebert, McAdam, Knott & Irwin, 1967) also linked the CNV to expectancy, but believed it had a strong motivational component, as larger CNVs were associated with increased effort, whether mental (to detect S2) or muscular (button pressure).

The CNV complex. While the hypothesized mental states accompanying the CNV are intuitively appealing, they all imply that the CNV is a unitary phenomenon. More recent evidence suggests that the CNV is the sum of several subcomponent negative waves. Moreover,

the negative shift may not even be contingent on the association of S1 and S2.

The concept of a nonunitary CNV was first broached by Loveless and Sanford (1974). They discovered that when the S1-S2 interval was longer than the paradigmatic 1-2 seconds, two distinct components could be isolated. As shown in the top portion of Figure 1-1, an early component is maximal at frontal locations. Because this response seemed to represent orientation to the warning stimulus, Loveless and Sanford called it the "O-wave." A later central-parietal component, seen in the middle and bottom portions of Figure 1-1, seemed to reflect expectancy or preparedness for the response. When subjects were not required to make a motor response to S2, this later negativity dropped out. Like Walter before them, they termed this later potential the E-wave, to denote its putative relationship to expectancy. When the interval between S1 and S2 was decreased, the "O-" and "E-" waves merged into the familiar CNV wave, perhaps more accurately called the CNV complex.

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

As reviewed by Loveless (1979) and Rohrbaugh and Gaillard (1983), the biphasic nature of the long ISI CNV has been replicated many times, with various methodologies. One of the more advanced of these methods is principal component analysis (PCA; see Donchin and Heffley (1978) for a review of the technique). For example, McCallum and Curry (1981) subjected CNV waveforms recorded in simple and choice RT paradigms to PCA, discovering "an almost embarrassing plethora of late

slow wave features" which could be systematically varied through manipulation of experimental variables. Interestingly, a unified CNV factor consistently appeared, largest when subjects responded to S2.

Although the amount of variance accounted for by the CNV factor was not reported, it was the first factor to emerge in 6 of 7 conditions.

Based on the PCA, these authors concluded that there was not one, but a whole family of late waves comprising the CNV complex.

Sanquist, Beatty and Lindsay (1981) attempted to associate some of these components with psychological processes. Their PCA indicated that the early limb of the CNV, the O-wave of Loveless and Sanford (1974), was itself composed of two subcomponents. An early frontal negativity covaried with the amount of information carried in S1, while a second, more broad negativity reflected generalized orienting and arousal. A late, central-parietal negative shift or E-wave preceding S2 was interpreted as representing motor preparation for the reaction to S2.

Taken together, these results indicate that the CNV can be subdivided into at least two families of potentials: those generated by perceptual or decision-making process (eg. stimulus evaluation), and those related to anticipation of a motor event (response production). McAdam (1973) referred to this as the dichotomy between event-related potentials (ERPs) and response-related potentials (RRPs). If this is so, the late-arising E-wave may be indistinguishable from the earliest of the RRs, the readiness potential (RP). Originally called the Bereitschaftspotential (BP) by Deecke, Scheid and Kornhuber (1969), the RP is seen as a slow, negative-going potential arising 300-200 msec before a voluntary

response, peaking at the time of the response. The E-wave of the CNV and the RP share several qualities, including their ramp-like morphology (McAdam, 1973; McAdam, Knott & Rebert, 1969), and their susceptibility to modulation by psychological factors. Both potentials tend to increase with demands on attention, motivation, conation and expectancy (Deecke, Becker, Grozinger, Scheid & Kornhuber, 1973). In addition, the amplitude of both waves covaries with the amount of muscle effort required in speeded performance tasks. Finally, both the E-wave of the CNV and the readiness potential are attenuated or abolished when no motor response is required.

The distinction between the late CNV and the RP was made even less clear by a recent study by Libet, Wright and Gleason (1983). They had subjects perform CNV tasks which involved similar non-motor components (expectancy, attentiveness, general orienting), but differed in whether a motor or non-motor response was required. No CNV-like activity was seen in the non-motor conditions. The cognitive factor necessary for the appearance of the slow negative shift was present only in tasks which required preparation for a motor response.

Actual consummation of the movement was not necessary, however; the shift also appeared when the subject knew he would "veto" his intention to act shortly before the time for the motor response. Although Libet et al. concluded that the slow negative potential reflected a conative process of intending to act, the results could also be accounted for by the readiness potential.

Perhaps the most compelling evidence that the CNV is composed of separate O- and E-waves is the fact that CNV-like waveforms

(representing both long and short ISIs) can be synthesized by the simple addition of (1) responses to individual sensory stimuli (O-waves) and (2) readiness potentials (RPs; Rohrbaugh, Syndulko & Lindsley, 1976; Rohrbaugh, Syndulko, Sanquist & Lindsley, 1980). These individual responses were recorded in separate sessions, and neither required experimental contingency for their appearance. When the synthesized CNVs were compared to actual CNVs recorded from the same subjects in forewarned PT situations, they could not be distinguished visually. When both were subjected to PCA, both synthesized and actual CNVs produced factors corresponding to O-waves and RPs. In addition, when actual and synthesized CNVs were added in the covariance matrix, only 2 factors emerged; the O-wave and RP. Importantly, no significant differences could be found to statistically discriminate actual from synthesized waveforms.

Interestingly, it is the discoverer of the RP and his colleagues (Deecke, 1978a,b; Deecke et al., 1973) who most strenuously object to the identification of the late E-wave of the CNV with the RP. Deecke et al. argue that one of the most effective ways to differentiate the CNV and the RP is through the distribution of the potentials across the scalp. Unfortunately, many researchers record only from the vertex, making such comparisons impossible.

The scalp topography of the CNV E-wave is typically maximal at the vertex, slightly smaller in frontal areas, and smallest at parietal locations. The RP follows a similar gradient, but falls off anteriorly to a much greater extent. In some cases the RP actually becomes positive at the frontal poles (Deecke et al., 1969). Even these differences in the frontal topography can be accounted for if

one assumes that the CNV is the sum of a negative frontal wave (the O-wave) and the RP (Rohrbaugh & Gaillard, 1983). The frontal aspects of the O-wave would then combine with the more central and parietal RP to produce the familiar domed distribution of the CNV, maximal at the vertex.

Differences in the lateral distribution of the RP and the late CNV are less easily explained. The RP consistently shows a slight asymmetry, with greater negativity over the hemisphere contralateral to the impending motor activity (Vaughan, Costa & Ritter, 1968). This difference is more often found at central than at parietal locations (Deecke, 1978a), and is more pronounced at intracerebral electrodes (McCallum, 1978a). Recordings in the lateral plane indicate that the CNV is bilaterally symmetrical (Donchin, Ritter & McCallum, 1978).

The CNV and RT. The amplitude of the CNV has been found to be positively correlated with RT speed, with larger CNVs associated with faster RTs in within-subject comparisons (Hillyard, 1969; Rohrbaugh, Syndulko & Lindsley, 1976; Tecce & Scheff, 1969). In addition, treatments such as distraction which affected RT also usually altered CNV amplitude, indicating that CNV amplitude was related to attentiveness and phasic arousal. On the other hand, these correlations were typically much more modest when comparisons were made between subjects; that is, slower subjects did not necessarily have smaller CNVs (Connor & Lang, 1969; Waszak & Obrist, 1969). Tecce (1972) concluded that while a major function of the CNV was to facilitate the speed of response to the IS, the small amount of variance shared by CNV and RT measures indicated that other processes were also involved in CNV changes. A problem with these early studies

is that the CNV was considered a unitary waveform. Separation of the CNV into various components, such as the O- and E- waves, might explain the relatively low correlations between RT and CNV amplitude.

The CNV After Closed Head Injury

Because of the association between the CNV and orientation, attention, and response preparation, it would seem logical for investigators to use CNV paradigms to try to elucidate the nature of the slowing deficit after head injury. To date, three studies have tested head injured patients in CNV tasks.

Noting that a distracting tone produced a 4-fold reduction in the CNV of anxious, neurotic patients (McCallum & Walters, 1968), McCallum and Cummins (1973) used a similar paradigm among neurosurgical patients, including head injuries. Patients were divided into three groups, depending on whether lesions and their effects were localized or diffuse. Although head injuries comprised half of the diffuse group, notably absent were patients with diffuse injuries affecting more than one hemisphere, as might be produced by an acceleration/deceleration shearing injury or generalized brain swelling. Other than the need for neurosurgery, no data were presented on the severity of the head injuries.

Most head injured patients were classified as having localized lesions producing diffuse effects. The bulk of these patients had "negligible" asymmetry in their CNV. In contrast, marked asymmetry was common among patients with localized cortical lesions producing focal effects. Almost invariably these asymmetries consisted of an attenuated CNV over the affected hemisphere. The more diffuse the

location or effect of cortical lesions, the more widespread the attenuation of the CNV. In addition, the CNV was also affected by brainstem lesions, with the CNV significantly attenuated by pressure on the brainstem. However, when pressure was relieved, the CNV "rebounded" to supra-normal amplitudes.

Although McCallum and Cummins' (1973) results suggested that head injury induced a reduction in the CNV, these findings were not conclusive because of the mixture of etiologies. Only about 1/5 of the patients had suffered head injuries. Other etiologies included tumor, CVA, communicating hydrocephalous, and Parkinson's disease. In addition, because patients were grouped according to lesion location and effect, it is difficult to parcel out the effects of head injury per se on the CNV.

Results from Rizzo, Amabile, Caporali, Spadaro, Zanasi and Morocutti (1978) were more definitive. These authors tested 27 patients who had suffered traumatic head injuries at least 5 months prior to the time of testing. All suffered immediate coma, which lasted an average of 15 days (range = 2 - 90 days). Twenty-five patients had closed brain contusions; of these, five also had acute subdural hematomas. Two other patients had open head injuries. Rizzo et al. (1978) used a Go/No-Go paradigm in which S1 (a click) was followed 1500 msec later by the imperative stimulus, either a high or a low tone. Subjects responded only to the high tone (Go) and refrained from responding to the low tone (NoGo).

Although several measurements indicated that patient CNVs were smaller and later than control CNVs, only the area under the CNV curve showed a significant difference between the two groups. Because

recordings were obtained only from the vertex electrode, no data were available on the distribution of the potential in either group. In accord with McCallum and Cummins (1973), Rizzo et al. (1978) attributed their findings to "primary or secondary impairment of cortical and subcortical structures generating the CNV." Reaction time data were not presented.

The third study of the CNV after head injury was reported by Curry (1980). His conference paper briefly described four ERP paradigms, including a modified Go/No-Go auditory CNV paradigm somewhat different from that used by Rizzo et al. (1978). Curry (1980) reported that ERPs were generally aberrant among the head injured patients, who were tested as soon as possible after PTA. In fact, only 2 of the 25 patients had completely normal responses, as defined by 11 control subjects. Moreover, ERP abnormalities followed a gradient of injury severity, with specific abnormalities distinguishing the severe group (PTA > 7 days, $n = 6$) from moderate (PTA = 1 - 7 days, $n = 5$) and mild (PTA < 1 day, $n = 14$) groups. For example, like Rizzo et al. (1978) and McCallum and Cummins (1973), Curry (1980) noted an attenuated or absent CNV among 2 of the 6 severe injuries in the Go/No-Go paradigm. However, a more common finding was an unusually large CNV among patients in this paradigm. This result may have been due to Curry's modification of the CNV paradigm.

In its usual formulation, the first stimulus in a Go/No-Go CNV paradigm (S1) serves as a warning signal, priming the subject for the upcoming S2. This first stimulus is therefore sometimes called the warning stimulus (WS). In the paradigm used by Rizzo et al. (1978) and others, it is the second, imperative stimulus which indicates

whether or not a motor response is required. Among normals, a large CNV develops after WS, as the subject must prepare for the possible response after IS.

In Curry's modification of this paradigm, the first stimulus bore this information. Among Curry's normal controls, a large CNV appeared only after those WS which indicated a response was required to S2. In controls, there was no measurable CNV when WS indicated that S2 could be ignored. To differentiate between the two WS, they will be called WS-Go and WS-Stop, respectively.

In contrast to normals, a large CNV developed after both WS-Go and WS-Stop in at least half of each head injury group. This "exaggerated" CNV appeared in 7 of 14 "milds," 3 of 5 "moderates," and 3 of 6 "severes." However, in spite of an apparent preparation to respond to non-targets, Curry reported that patients behaviorally performed the task correctly. Unfortunately, no data for RT or accuracy were presented.

Curry (1980) suggested that this effect might represent the disinhibition of a process normally damped by frontal mechanisms, diffusely damaged by head injury. Although he presented no data, he also alluded to clinical information which indicated a relationship between exaggerated, attenuated or absent ERPs and functional deficits.

Summary

Severe closed head injury results in a variety of brain lesions and functional deficits. The literature in this field has tended to

concentrate on the acute patient, with the specific aim of predicting which patients have the best chance of making a satisfactory recovery (Giannotta et al., 1982). Several neurophysiological measures appear to be predictive of eventual outcome. One way to validate their apparent utility is to apply these neurophysiological tests to patients who have made a satisfactory recovery. One aspect of the current research involved the examination of neurosensory evoked potentials in relation to recovery from head injury.

In spite of the increasing number of survivors of severe head injury, considerably less is known about their long-term recovery. The contingent negative variation was utilized as a test of two possible deficits, "under-" and "over-processing," either of which might serve as an explanation of the behavioral slowing so common after CHI.

Because these types of studies are often criticized for a failure to adequately define the patient sample, the first study described in this dissertation attempts to demonstrate that the relatively small patient samples employed in the neurosensory and CNV studies were, in fact, typical of much larger patient populations.

Figure 1-1. Typical CNV waveform and associated behavioral response. The EEG was recorded for 2400 ms, beginning 400 ms before the first stimulus. Tracings represent averaged EEG recorded from midline frontal (Fz), central (Cz), and parietal (Pz) electrodes. In this paradigm WS indicated that the subject might have to respond following a second, imperative stimulus (Go). Of interest in this Figure is the scalp topography of the two major components of the CNV. At frontal and central electrodes, a large, broad component known as the O-wave is visible 300 - 700 ms after WS (triangle in top trace). As the recording of the EEG continued, the O-wave asymptoted at Fz. At Cz and Pz, the O-wave gave way to the E-wave (triangles in second and third traces). The O-wave continued to increase in amplitude until the Go stimulus. On the bottom tracing, the histogram of the subject's response time presented. Because this was a forewarned reaction time task, with a constant foreperiod, the distribution of RT tends to be positively skewed.

Table 1-1*

Glasgow Coma Scale (GCS) of Teasdale and Jennett (1974)

<u>Eye Opening</u>	Spontaneous	4
	To verbal command	3
	To pain	2
	None	1
<u>Verbal Response</u>	Oriented	5
	Confused	4
	Inappropriate words	3
	Incomprehensible sounds	2
	No verbal response	1
<u>Best Motor Response</u>	Follows commands	6
	Localizes stimuli	5
	Withdraws	4
	Decorticate (flexion)	
	posturing	3
	Decerebrate (extension)	
	posturing	2
	No movement	1

Chapter 2

Study I

Demography of Closed Head Injury Patients

Because of the rather elaborate nature of the studies involved in this dissertation, relatively few patients could be tested. As a consequence, there may be some concern as to whether the tested patients are representative of, on the one hand, local head injured patients, and, perhaps more importantly, North American head injuries. If results obtained in this research are to be generalized to larger groups of head injuries, the demography of the participating patients must be determined, and compared to that of the larger populations from which they were drawn. The purpose of this chapter is to demonstrate that those patients tested were representative of a larger group of consecutive admissions, and that the composition of this larger group was very similar to that described in large-scale epidemiological studies, such as those referred to in the Introduction.

Method

Patient Population

A list of patients treated over the last several years was sought from St. Vincent Hospital, the major head injury rehabilitation center in Ottawa. The obtained list included 67 patients treated as

inpatients and/or outpatients since 1978: 14 females and 53 males.

The Medical Advisory Committee of the hospital approved access to the patients and their medical records, as well as hospital facilities and equipment (Appendices A and B).

From this initial population, it was decided that only those patients who had sustained their injury less than 7 years previously, and lived in close proximity to Ottawa would be tested. Twenty-two patients met these criteria. Thus, three patient groups are described in this chapter: 67 consecutive head injury admissions at St. Vincent Hospital, 22 of whom met the criteria for further testing, and 45 of whom did not.

Demographic Variables

Several measures of the makeup of these patient groups were obtained from medical records. In addition to personal data such as birth date and education level attained, a great deal of information was gathered concerning the accident in which the head injury was sustained. These data included the date and ~~often~~ time of injury, as well as the mechanism of injury (automobile, bicycle, etc.). The age at injury was determined by subtracting the date of birth from the date of injury. Time since injury was also calculated by subtracting the date of injury from a later date. For patients who participated in the neurosensory screening, the second date was the date of sensory evoked potential testing. For patients who were not tested, the second date was arbitrarily set at May 1, 1984, when neurosensory screening began.

Several measures of injury severity were made. Each patient's depth of coma was estimated using the Glasgow Coma Scale (GCS).

Because very few cases had a coma score noted, the GCS was in most instances estimated from written observations made at admission (usually an emergency room). Typically, admission records indicated the status of pupillary, corneal and deep tendon reflexes, and the minimum stimulus required to elicit any type of response, with the response noted.

Duration of coma was also obtained from the medical charts. In some instances the duration of coma was recorded in the discharge summary of the acute care center or rehabilitation setting. In most cases, it was obtained from detailed reading of the daily progress notes. In the latter cases, coma duration was taken as the time between injury and the first chart date which recorded key phrases such as "regained consciousness," "woke up," or "responded appropriately."

Patients' time in post-traumatic amnesia (PTA) was also obtained from their medical records. PTA was defined as the period between injury and the return of continuous memory for ongoing events. Because the end of PTA is difficult to establish without testing for it, only cases in which PTA was specifically evaluated were included.

In order to obtain estimates of the degree of recovery patients had made in the years since their injury, four independent raters completed two outcome scales for those patients with whom they were familiar. The scales used were the Glasgow Outcome Scale (GOS; Jennett & Bond, 1975; Appendix C) and the Disability Rating Scale (DRS; Rappaport, et al., 1981; Appendix D). Raters included the patient's

physiatrist, his occupational therapist, his psychometrist, and, in the case of tested patients, the experimenter. Sixteen patients were known to and rated by each of the four independent raters.

Statistical Analyses

Univariate statistics were computed for each of the three groups (67 consecutive admissions, 22 tested patients, and 45 untested patients) on each variable. To determine whether tested and untested patients differed, two-sample t tests were performed on each demographic variable: age at injury, education, Glasgow Coma Scale, duration of coma, duration of post-traumatic amnesia, time since injury, Glasgow Outcome Score, and Disability Rating Score. The equality of variance assumption was tested using Levene's test. Finally, parametric (Pearson's r) and non-parametric (Kendall's τ) correlations were computed for all pairs of demographic variables using the pool of all patients' data. Kendall's statistic was used when one of the variables was ordinal or had very few levels. The inter-rater reliability of the 4 judges using the Glasgow Outcome Scale and the Disability Rating Scale was computed from the Spearman-Brown prediction formula (Winer, 1971). For all statistical tests, the significance level was set at $p = .01$.

Results

Descriptive statistics for the entire group of 67 patients was

well as for 22 tested and 43 untested patients, are presented in Table 2-1.

----- Table 2-1 about here -----

Demographic Data

Sex of Patients. While the male/female ratio in the general population is approximately 100/100, among the patients in the present sample was 170/11. This ratio was 144/11 among tested patients, and 4/11 among the untested patients.

Age at Injury. At the time of injury, potential patients $N = 67$ ranged in age from 16 years, 6 months to 64 years. $M = 26$ years; $SD = 12$ years, 2 months. Tested patients $n = 22$ were on average slightly younger ($M = 23$ years, 2 months, $SD = 7$ years, 2 months) ranging in age from 17 years, 2 months to 47 years, one month. There was no significant difference between the tested and untested patient groups on age at injury, $t(65) = 0.4$.

Education. Among all patients, education ranged from grade 9 to the Ph.D. level. $M = 13.7$ years; $SD = 1.9$ years. Average education among tested patients was 13.7 years, ranging from grade 9 to the Master's level ($SD = 1.9$ years). The difference in education between tested and untested groups was not significant, $t(65) = -1.5$.

Mechanism of Injury. As shown in Figure 2-1, 41 of the 67 consecutive admissions sustained their head injury as either the driver or passenger in an automobile or truck. Other motor vehicle accidents (MVAs) included car or bus collisions in which the patient was on a motorcycle ($n = 9$), bicycle ($n = 3$), or on foot ($n = 4$). The

sample also included 2 victims of skidoo accidents, 2 sports injuries, and 1 farm accident. Victims of falls and assault were not included. As also shown in the Figure, the proportion of tested patients injured by these mechanisms was very similar. Figure 2-2 shows the range of age at injury as a function of the patient's conveyance. As can be observed, the only notable trend is for patients injured in motor vehicle and bicycle accidents to be younger than those using other forms of transportation.

----- Figures 2-1 and 2-2 about here -----

Time of Injury. As shown in Figure 2-3, most of the motor vehicle accidents occurred on the weekend, regardless of the patient's conveyance. Data in this figure represent 70 MVA-induced head injuries.

----- Figure 2-3 about here -----

Severity of Injury

Glasgow Coma Scale. Enough data were present to estimate the initial GCS for 56 of the 67 patients. The average estimated GCS of all patients was 5.6, ranging from 4 to 8 ($SD = 1.6$). Tested patients tended to have slightly lower scores ($M = 4.86$), with a more restricted range (4 to 7; $SD = .94$). The difference between tested and untested patients on the GCS was significant, $t(54) = 3.05$, $p < .01$. The distribution of scores for all patients and for tested patients is shown in Figure 2-4.

----- Figure 2-4 about here -----

Duration of coma among all patients averaged 35.6 days, ranging from one day to 150 days ($SD = 34$ days). Tested patients were in coma slightly less time, for a mean of 28.2 days (range = 1 to 75 days; $SD = 27$ days). The difference in coma duration between tested and untested patients did not reach significance, $t(65) = 1.25$.

PTA. At least 67 patients, 47 patients had PTA duration recorded in their medical or neuropsychological reports. The average PTA for all patients was 80 days, with a range of from 1 day to 1 year ($SD = 80$ days). Among tested patients, average PTA was 85 days, ranging from 10 days to one year ($SD = 80$ days). This difference was not significant, $t(65) = 1.07$.

Outcome Measures

Time Since Injury. Mean time since injury (TSI) for all patients was 3 years, 10 months, ranging from 6 months to over 23 years ($SD = 3$ years, 5 months). Among tested patients, average TSI was 3 years, 2 months, (range = 8 months to 6 years, 4 months, $SD = 1$ year, 4 months). The difference in time since injury between tested and untested patients was not significant, $t(65) = 1.03$.

Outcome scales. At least two raters judged a total of 36 patients on both the Glasgow Outcome Scale and the Disability Rating Scale; 14 untested patients and the 22 tested patients. The distribution of patients' scores on these scales is given in Figure 2-5.

----- Figure 2-5 about here -----

Sixteen patients were rated by all four raters on both scales. Inter-rater reliability on the GOS was .90. On this scale, 22 patients were rated as having made Good Recoveries, 10 were rated as moderately disabled, and 4 were rated as Severely Disabled. Of the tested patients, 13 were considered Good Recoveries, 7 were Moderately Disabled, and 2 were Severely Disabled. The difference between tested and untested patients on the GOS was not significant, $t(33) = .15$.

Similar results were obtained on the more finely graduated Disability Rating Scale. Inter-rater reliability between the four judges using the DRS was .89. Two patients were considered without disability, 15 had mild disability, 15 were partially disabled, 2 were moderately disabled, and 2 patients' disability was considered to be moderately severe. Among tested patients, 1 patient was considered without disability, 8 were mildly disabled, 11 were partially disabled, 1 moderately disabled, and 1 disability was judged moderately severe. In addition, because the DRS uses an interval level of measurement, a mean could be calculated for the scale. Among all 36 patients, the mean was 2.3 (range 0 to 11; $SD = 2.2$). For tested patients, the mean was 2.4 (range 0 to 11; $SD = 2.4$). The difference between tested and untested patients on the DRS was not significant, $t(33) = -.27$.

Correlations in Patient Demography.

As shown in Table 2-2, several significant correlations were obtained. These measures fell into 3 categories: premorbid variables (age at injury, education), measures of injury severity (coma scale, coma duration, PTA duration), and outcome measures (time since injury, GOS, DRS). There were several correlations between variables of different categories, as well as among variables within each category.

----- Table 2-2 about here -----

Few measures were associated with premorbid variables. Age at injury correlated significantly with outcome, as measured by the Glasgow Outcome Scale. The association was nearly as strong with the Disability Rating Scale.

In addition, there were several significant correlations among measures of injury severity. For instance, depth of coma, as measured by GCS, was significantly correlated with the duration of coma. A significant correlation was also found between initial coma depth and length of PTA. Coma duration was also significantly associated with PTA. Finally, initial coma depth was significantly correlated with outcome, as measured by the DRS.

Among outcome measures, a significant correlation was found between scores obtained on the GOS and those on the DRS. In addition, both of these measures were highly correlated with measures of the severity of injury, including coma depth and the duration of PTA.

Discussion

These data indicate that patients tested in subsequent parts of this research were indeed very similar to the larger sample of consecutive admissions from which they were drawn. The tested sample was representative of the larger group on premorbid data, such as education and age at injury, as well as on measures of injury severity and outcome.

In addition, the distribution of several variables corresponds well to that reported in the literature with much larger groups. For example, Marshall et al. (1983) described the composition of a sample of 581 cases of severe CHI in the United States. One of their principle findings was that young men are the most frequent victims of head injuries. Similar findings have recently been reported in a much larger ($N = 3000$) Canadian sample which incorporated all levels of injury severity (Parkinson et al., 1985). The much smaller Ottawa sample described in this chapter closely approximates these other distributions. Figure 2-6 shows the proportion of male and female head injuries in various age categories found by Marshall et al. For comparison, data from the present study are also shown in the Figure, including all 67 consecutive admissions and the 22 tested patients. While the reduced number of very young and very old patients (who are admitted to other rehabilitation centers in the area) causes the distributions of the local samples to be somewhat more leptokurtic, the overall distribution of all three groups is remarkably similar,

with most injuries sustained by 15-29 year old males. Thus, the age of the tested patients was highly representative of the larger population of head injuries in North America.

----- Figure 2-6 about here -----

Also in common with larger studies (Annegers et al., 1980; Parkinson et al., 1985), most of the patients in the present study sustained their injuries in motor vehicle accidents (MVAs), whether in or on a motor vehicle, or struck by one. Fully 95% of all patients surveyed were injured in MVAs; all 22 of the tested patients were injured in this manner.

On average, patients obtained a high school level education, with tested patients slightly better educated. The nonsignificant correlation between age at injury and education suggests that most patients had completed their education prior to their injury. The finding that victims of head injury tend to be less well educated is similar to that of Parkinson et al. (1985), who found an inverse relationship between earning capacity and frequency of head injury.

Neither age at injury nor education were correlated with injury severity, perhaps due to the restricted range of the latter; all injuries were severe. On the other hand, age at injury was significantly associated with outcome, with younger patients achieving better outcomes than older patients. This result was also reported by Jennett et al. (1979). They found that patients in three age categories had significantly different outcomes on the GOS, with older patients fairing worse.

At the time of this research, an average of about three years had elapsed since most patients' accidents, with time since injury ranging over several years for individual cases. Time since injury had little relationship to other variables, including outcome. This finding is in accord with those of Jennett et al. (1981), who found that 90% of severely head injured patients reached their final outcome level of disability within 6 months of injury.

U All measures of injury severity indicated that the patients in this research were severely injured. Coma is typically defined as a score of 8 or less on the Glasgow Coma Scale; severe closed head injury is assumed when the GCS score remains below 8 for 6 or more hours (Levin, et al., 1982). Patients in the current study clearly met these criteria; on average, patients had GCS scores of 5.6, with all patients' scores remaining below 8 for at least a day. In fact, most patients remained in coma for weeks or months. The average coma duration was 35 days. Another measure of injury severity is the duration of PTA. In the current sample, PTA for both tested and untested groups was about 12 weeks. In Gennarelli's (1982) classification, this duration is consistent with a diffuse white matter shearing injury, presumably induced by acceleration/deceleration (recall that nearly all patients were injured in traffic accidents).

Considered separately, each of these measures of injury severity indicate that the patients in the current sample sustained severe closed head injuries. In addition, however, the relatively high intercorrelations between these measures provide insight into the nature of severe closed head injury. There was a significant

correlation between depth of coma at admission and the duration of coma, indicating that patients initially deep in coma tended to improve only slowly. The only other known study of prolonged unconsciousness, that of Bricolo et al. (1980), did not use the GCS in evaluating depth of coma. However, they did report that most patients with coma longer than two weeks initially had comas of less than extreme severity, suggesting an inverse relationship between depth of coma and coma duration, contradictory to the present findings. There was also a significant positive correlation between depth of coma and duration of PTA in the present study, indicating that patients initially deep in coma had long PTAs. Finally, duration of coma and duration of PTA were significantly correlated, suggesting that long comas resolved into long periods of PTA. In other studies, the relationship between coma and PTA has not been as high. For example, von Wovern (1966) found a lack of correspondence between the duration of coma and amnesia. However, his definition of coma was not as precise as that used in the current study, and there were several patients in his study over the age of 50. Older patients seem particularly prone to persistent memory problems, even after rather minor head injury (Levin, et al., 1982).

Thus, the relationships between measures of injury severity indicate that the patient who is initially deep in coma will also have a relatively long period of unconsciousness, which in turn will resolve into a long period of post-traumatic amnesia. Not surprisingly, the eventual outcome of such a patient is rarely good.

There were several high correlations between acute measures and outcome measures, indicating that more severe injuries are associated

with poorer outcomes. For example, the negative correlation between the GCS and the DRS suggests that patients initially deep in coma may recover, but will have significant deficits. Significant relationships were also found between PTA duration and both the DRS and the GOS, indicating long PTA is associated with poor recovery. Persistent problems would likely include notable disruption of memory (Levin et al., 1982).

While many significant correlations were found, it should be noted that the degree of variance shared between variables was generally modest. For example, although a significant relation was found between duration of coma and duration of PTA, the Pearson r of .55 indicates that only about 30% of the variance in the duration of PTA could be explained by the time spent in coma; 70% remains unexplained.

In contrast, the two outcome scales were highly correlated, with 64% of the variance of one scale accounted for by the other. However, the scales were not completely redundant. The DRS yielded high correlations with PTA, with which the GOS was only marginally associated, and the GOS was significantly correlated with age at injury, while the DRS was not. The inter-rater reliabilities of the two scales was nearly identical, although not as high as reported in other studies (Hall et al., 1985; Jennett et al., 1981; Rappaport et al., 1982). This lowered reliability may have been due to the small amount of training the raters received, and suggests that there may be some disagreement between less highly trained raters. On the whole, it seems that the continued use of both scales is warranted. However, because the DRS includes a Glasgow Coma Scale, it may be more suitable

for repeated administrations in the hospital setting, as the comatose patient regains consciousness.

In summary, the demographic data obtained on the 67 consecutive admissions to St. Vincent Hospital indicates that these patients were very similar to patients in large epidemiological studies of severe closed head injury. These similarities hold whether one considers biographic data, injury severity, or outcome. Moreover, the 22 patients selected for the current study were not different from the rest of the St. Vincent population. Therefore, it is reasonable to generalize results obtained in the following studies to other, larger populations, including not just the patients of St. Vincent, but all survivors of severe closed head injury in North America.

Figure 2-1. Mechanisms of patients' injuries. Data on the left are from 67 consecutive severe closed head injury admissions at St. Vincent Hospital, including the 22 patients tested in the current study. These 22 tested patients are shown separately on the right. Nearly all patients sustained their injuries in motor vehicle accidents (MVAs), whether as the occupant or rider of a motor vehicle, or struck by one. Also included were skidoo accidents, sports injuries, and a farm accident. All head injuries were of the sudden acceleration/ deceleration type, thought to induce diffuse shearing injuries.

Auto/Truck Occupants

Motorcyclists 9 13.4%

Pedestrians 9 13.4%

Bicyclists 3 4.5%

Others 5 7.5%

Auto/Truck Occupants

Motorcyclists 2 9.1%

Pedestrians 2 9.1%

Bicyclists 2 9.1%

Others 1 4.5%

TESTED PATIENTS (N=22)

Figure 2-2. Patient age at injury as a function of conveyance. Mean and standard deviation of patients' age at injury are given for 67 consecutive admissions of severe closed head injury (heavy lines) and the 22 patients tested in the current study (light lines). Groups are similar in age at injury, with few very young or very old individuals. Regardless of conveyance, patients tended to be young, with bicyclists and motorcyclists somewhat younger than the group average.

PATIENT
GROUP

ALL (N=67)

+1 S.D.

Mean

-1 S.D.

TESTED (N=23)

+1 S.D.

Mean

-1 S.D.

Patient's Conveyance

Figure 2-3. Day of week on which 59 MVA-induced head injuries occurred. Three types of conveyance are considered separately. Independent of the conveyance, most MVAs occurred on the weekend.

Figure 2-4. Estimated Glasgow Coma Score at admission. Data are presented for 56 consecutive admissions, of which 22 were tested in this study. Scores were retrospectively estimated from emergency room admission notes. For all patients, the average estimated GCS was 5.6. For the 22 tested patients, the average GCS was significantly lower, at 4.9. Most patients' scores were in the lower range of the scale, which extends to a normal, conscious score of 15. In this study, coma was defined as a score of 8 or less for more than 8 hours.

Figure 2-5. Outcomes for 36 survivors of severe closed head injury.

Patients were rated on both the Glasgow Outcome Scale (GOS; top) and the Disability Rating Scale (DRS; bottom) by up to 4 independent raters familiar with the case. Most patients made satisfactory recoveries, indicated by good recovery or moderate disability on the GOS or less than moderate disability on the DRS. The DRS has several additional categories of disability into which no patients were classified (see Appendix B). There was no significant difference on outcome between tested and untested patients.

Figure 2-6. Proportion of head injuries by age and sex found by Marshall et al. (1983) and in the present study. The data of Marshall et al. (top panel) are from 581 consecutive admissions of severe closed head injury to 6 clinical head-injury centers in the United States, over a 2 year period. Patients were included in that survey if they had a GCS score of 8 or less within 48 hours of admission. Approximately 75% of the patients were male, 50% were aged between 15 and 29 years, and 67% were victims of motor vehicle accidents. Of the 67 consecutive admissions considered in the present study (middle panel), 82% were male, 73% were aged between 15 and 29 years at the time of injury, and 93% were injured in MVAs. Of the 22 patients actually tested in this study (bottom panel), 77% were males, 82% were aged 15 to 29 years at injury, and 95% were injured in MVAs. Although there were more males than females in each age group in all three samples, the age distributions of males and females was very similar. The distributions of patients in the current sample are somewhat more peaked than those of Marshall et al. because there were fewer very young and very old patients.

Marshall, 1985

Males (N=10)

Females (N=18)

All Patients

Males (N=55)

Females (N=12)

Tested Patients

Males (N=17)

Females (N=5)

Table 2-4

Descriptive Statistics for
67 Consecutive Severe Closed Head Injury Admissions

	All Patients	Untested Patients	Tested Patients
Age at Injury (years)			
Cases	67	45	22
Mean	26.0	27.2	23.7
Std. Dev.	9.7	10.5	7.4
Education (years)			
Cases	65	43	22
Mean	12.0	11.2	13.7
Std. Dev.	2.9	2.5	2.9
Glasgow Coma Scale			
Cases	56	34	22
Mean	5.6	6.1	4.9
Std. Dev.	1.6	1.8	0.9
Coma Duration (days)			
Cases	67	45	22
Mean	35.7	39.3	28.2
Std. Dev.	34.2	28.7	21.3
PTA (days)			
Cases	45	26	19
Mean	86.0	86.8	85.0
Std. Dev.	85.8	90.8	80.8
Time Since Injury (years)			
Cases	67	45	22
Mean	3.8	4.1	3.2
Std. Dev.	3.4	4.0	1.3
Glasgow Outcome Scale			
Cases	36	14	22
Mean	1.5	1.5	1.5
Std. Dev.	0.7	0.8	0.7
Disability Rating Scale			
Cases	36	14	22
Mean	2.3	2.1	2.4
Std. Dev.	2.2	2.1	2.3

Table 2-2

Correlations between Patient Demographic Variables

	Age at Injury	Educ.	Glasgow Coma Scale	Duration of Coma	PIA	Time Since Injury	Glasgow Outcome Scale	Disabil Rating Scale
Age at Injury		.216 (64) .043	.045 (56) .330	-.082 (67) .254	.019 (45) .450	-.120 (67) .166	.321 (36) .009*	.254 (36) .023
Education	.216 (64) .043		-.190 (53) .041	-.086 (64) .248	-.265 (43) .043	.031 (64) .404	-.099 (36) .249	-.180 (36) .173
Glasgow Coma Scale	.044 (56) .330	-.190 (53) .041		-.328 (56) .001*	-.299 (39) .009*	-.079 (56) .218	-.318 (32) .022	-.362 (32) .008*
Duration of Coma	-.082 (67) .254	-.086 (64) .248	-.328 (56) .001*		.551 (45) .000+	.159 (67) .099	.193 (36) -.81	.156 (36) .116
Post- Traumatic Amnesia	.019 (45) .450	-.265 (43) .043	-.299 (39) .009*	.551 (45) .000+		.019 (45) .452	.484 (29) .001*	.410 (29) .003*
Time Since Injury	-.120 (67) .166	.031 (64) .404	-.079 (56) .218	.159 (67) .099	.018 (45) .452		.039 (36) .388	-.114 (36) .187
Glasgow Outcome Scale	.321 (36) .009*	-.099 (35) .249	-.318 (32) .022	.193 (36) .081	.484 (29) .001*	.039 (36) .388		.799 (36) .001*
Disability Rating Scale	.254 (36) .023	-.130 (35) .173	-.362 (32) .008*	.156 (36) .116	.410 (29) .003*	-.114 (36) .187	.799 (36) .001*	

 : Corr. coeffic. :
 Key: : (N) :
 : Probability :

+ Pearson product-moment correlation $p < .01$

* Kendall's tau rank-order correlation $p < .01$

Chapter 3

Study IINeurosensory Screening

In order to reduce the possibility that slowed performance and aberrant CNVs (the major concern of Study III) result from peripheral degradation of sensory information, the integrity of sensory systems was tested. The brainstem auditory evoked potential (BAEP) is able to monitor functioning of the peripheral auditory nerve as well as brainstem relay centers. Similarly, the somatosensory evoked potential (SEP) is employed to monitor peripheral and central nervous system relay centers in that modality. Amongst the latter are brainstem and primary cortical regions. Thus, both the auditory and somatosensory evoked potential techniques provide a means of verifying both peripheral sensory nerve and brainstem functioning. Although significant neurological deficits can coexist with normal EPs, significantly abnormal EPs are indicative of functional disruption of the sensory system involved. In addition, because the auditory modality was used in later testing of the CNV, audiograms were also collected from all subjects.

Short-latency (< 50 ms post-stimulus) evoked potentials (EPs) are determined by the interaction of external stimulus parameters and the integrity of peripheral and central aspects of the sensory system under investigation. These responses are largely independent of anesthesia, sleep, attention, and habituation, but bear log-linear relationships to psychophysical magnitude estimates of stimulus

2

1.0

1.1

1.25

1.4

1.6

1.8

2.0

2.2

2.5

2.8

3.2

3.6

4.0

4.5

5.0

5.6

6.3

7.1

8.0

9.0

10.0

11.2

12.5

14.0

16.0

18.0

intensity (Wilson & Stelmack, 1982). Thus, variation in either BAEP or SEP would be independent of the level of attention and arousal in the head-injured patient. Because of their robustness, several authors have cited the usefulness of EPs in neurosensory diagnosis (e.g. Chiappa & Ropper, 1982; Greenberg & Ducker, 1982), including acute head injury (Goldie et al., 1981; Greenberg et al. 1982; Lindsay, Carlin, Kennedy, Fry, McInnes & Teasdale, 1981; Pfurtscheller et al., 1985).

Brainstem auditory evoked potentials (BAEPs). Responses evoked in the first 10 ms after an abrupt auditory stimulus are highly consistent between and within normal subjects, and are clearly associated with auditory processing in the cochlea and brainstem (Picton, Stapells & Campbell, 1981; Stockard, Stockard & Sharbrough, 1980). While it is generally agreed that peak I represents the cochlear nerve compound action potential, dipole vector analysis in two (Picton, et al., 1981) and three (Ino & Mizoi, 1980; Williston, Jewett & Martin, 1981) dimensions suggest that peaks II-VI do not represent specific generators, but are overlapping fields from several different sources. These sources probably include auditory nerve fibers, cochlear nuclei, the superior olivary complexes, trapezoid bodies, and the lateral lemnisci. Peak V almost surely represents activity in the lateral lemniscus and/or midbrain collicular regions (Achor & Starr, 1980a,b; Buchwald, 1981; Stockard & Rossiter, 1977). The brainstem response thus has clear application in neurology (e.g. Rowe, 1981) and audiology (Picton & Smith, 1978).

A number of laboratories have established the peak I to peak V latency difference to be approximately 4.0 ms. Since peak I

originates in the auditory nerve (in the peripheral nervous system), and peak V in the midbrain region of the central nervous system, the I-V interpeak latency (IPL) is often used as a measure of central conduction time. Therefore, in the present study, this IPL was used in conjunction with results from an audiogram to measure the integrity of the peripheral and brainstem auditory system. A delayed peak I might be indicative of damage to the ear mechanism itself or the auditory nerve. If peak I is normal, but peak V delayed (i.e., an unusually long I-V IPL), brainstem damage would be suggested.

Somatosensory evoked potentials (SEPs). Most investigators now agree that the responses recorded in the first 50 ms after stimulation of the median nerve at the wrist represent activation of the lemniscal pathways. Although there is some controversy over the specific generators involved, components have been attributed to serial activation of the brachial plexus (N9), dorsal columns (P12), medial lemniscus (N14), thalamo-cortical radiations (N20) and primary somatosensory cortex (P22; see Cracco, Anziska, Cracco, Vas, Rossini & Maccabee 1982; Desmedt & Cheron, 1982; Kimura & Yamada, 1982; Suzuki & Mayanagi, 1984; Wiederholt, Meyer-Hardting, Budnick, & McKeown, 1982). In order to investigate the integrity of rostral brainstem structures in patients, the latency of the somatosensory evoked potential was recorded from several locations along this path.

The use of short latency EPs has largely been restricted to prognosticating from acute states, with few long-term studies of sensory EPs after CHI. Greenberg et al. (1977b) reported multimodality EPs recorded as late as 2 1/2 years post-trauma, but the bulk of their data was obtained on mean days 3 and 14 post-trauma. No

mention was made of how EPs recorded late in recovery correlated with those recorded in acute stages, or concurrent behavioral recovery. Rappaport et al. (1981b) reported that the relationship between EP abnormalities and disability was time-limited. Sixty days after injury, the relationship between EP abnormality and disability was no longer significant; in at least one case, EP abnormalities persisted in the face of functional recovery to the premorbid level.

In the present study, EPs were employed as an initial screening device to assess the functional integrity of auditory and somatosensory brainstem structures. As most patients were rated as having made satisfactory recoveries on the Glasgow Outcome Scale and the Disability Rating Scales, it was expected that most patients would have normal brainstem responses.

Method

Subjects

Patients. Because it was not feasible to test all 67 patients in the group of outpatients, it was decided that only patients who had sustained their injury less than 7 years prior to the starting date of the present study and who lived in close proximity to Ottawa would be included. Twenty-two patients were eventually tested in the screening sessions. The make-up of this sample was described in the preceding chapter.

Controls. A control group of 12 young adults (6 men, 6 women) was matched in age with prospective patients. In past sensory evoked potential studies in this and other labs, level of education has not

been shown to covary with these measures. Therefore, no attempt was made to control for this factor. It is unlikely that educational level or cognitive ability would influence functioning at "lower" levels of the brain. At the time of testing, the average age of male controls was 28 years, 0 months ($SD = 3$ years, 11 months), while the average age of female controls was 26 years, 11 months ($SD = 4$ years, 2 months). This difference was not significant. Collapsed across sex, the mean age of controls was 27 years, 6 months ($SD = 3$ years, 11 months). This was not significantly different from the age of patients at the time of the evoked potential test (mean for male patients = 26 years, 8 months, $SD = 7$ years, 11 months; mean for female patients = 23 years, 10 months, $SD = 2$ years, 11 months; overall patient mean = 26 years, 1 month; $SD = 7$ years, 1 month).

Both patient and control subjects were paid \$20.00 for participating in this study. Informed consent (Appendix E) was obtained before the testing, which was carried out in a single 3 hour session.

Apparatus and Procedure

Auditory and somatosensory evoked potentials were gathered in the Physical Medicine and Rehabilitation Unit of St. Vincent Hospital, using a TECA (Medelec) clinical averager. A TECA model ST-10 stimulus generator provided auditory and somatosensory stimuli. Stimulus and recording parameters similar to those used in several other labs were employed to assure generalizability.

Placement of scalp electrodes followed the International 10-20 system (Jasper, 1958). Prior to application of electrodes, the scalp

was prepped with a conductive, abrasive, adhesive paste (Omni Prep). To ensure good conduction of EEG signals, electrode paste (Grass EC-2) was also rubbed into the skin. Gold-plated Grass cup electrodes were filled with electrode paste before being taped to the head (3M Micropore surgical tape). Using this technique, inter-electrode impedances were consistently maintained below 2000 Ohms.

BAEP. Prior to the start of testing, a pilot study was carried out to calibrate the auditory stimulus generator. Thresholds were established for 10 young adults. Stimulus intensity in BAEP testing was set relative to this normal hearing level (nHL). Rarefaction 0.1 ms duration clicks were presented monaurally at a rate of 10/s, at an intensity of 80 dB nHL. Continuous, 70 dB nHL white noise was presented to the opposite ear to mask bone conduction of the stimulus to the contralateral side. EEG signals were recorded from Cz and referred to the ipsilateral low mastoid, to avoid possible myogenic artifact (Stapells & Picton, 1981). Filter settings were 100 and 3000 Hz. A frontopolar electrode served as ground. Averaging began at stimulus onset and continued for 10.24 ms, consisting of 512 data points (i.e., a dwell time of 20 usec). Trials in which EEG exceeded 20 uV were considered as artifact and thus rejected from the ongoing average. Averages were based on 2048 responses, the entire procedure being repeated a second time to assure replicability of the response. Left and right ears were tested on separate runs. Absolute and interpeak latencies of peaks I and V were determined from the average of the two recordings, using the on-line cursor system of the TECA averager. In addition, a hard copy of all BAEPs was plotted for later off-line verification.

SEP. The somatosensory evoked potential was recorded to a train of 5/sec constant current square wave pulses (.1 ms), presented to the median nerve at the wrist. The stimulating electrode (cathode) was placed over the nerve, 2 cm proximal to the wrist crease. The anode was placed 3 cm distal to the cathode, lateral to the median nerve. A large ground electrode was placed proximal to the stimulating electrode on the forearm. Sensory and motor (thumb twitch) thresholds were determined, with stimulation 10% above motor threshold.

After several pilot recordings, four electrode montages were chosen. Active electrodes and their references included ipsilateral Erb's point vs Fpz, CV7 vs Fpz, contralateral central scalp (C3 or C4) vs contralateral Erb's point, and C3 or C4 vs Fpz. Averaging began at stimulus onset, and continued for 51.2 ms, consisting of 512 data points (i.e., a dwell time of 100 usec). Trials in which the EEG exceeded 20 μ V were automatically rejected. Left and right median nerves were stimulated on separate runs. Measurements were taken from the average of two replications, each based on 2048 non-rejected trials. Measured responses included peripheral brachial plexus components P8 and N9, the medullary dorsal column component P12, the brainstem medial lemniscus component N14, early primary cortical components N20 and P22, and late cortical components N30 and P40. Median nerve conduction velocity was also determined by dividing the distance between the cathode of the stimulating electrode and the electrode over Erb's point by the latency of the peak recorded over Erb's point.

Audiogram. Because stimuli for the CNV task were presented in

the auditory modality, all subjects were administered an 11- frequency audiogram (ISO 1964), using the method of limits.

Screening procedure. To reduce the possibility of including subjects with brainstem dysfunction in the cognitive tasks of Study III, patients were excluded from CNV testing if evoked potential evidence was suggestive of brainstem damage. The following screening procedure was used. For all responses, when sex differences in the control data were not significant, the combined data from both sexes were used in determining the normalcy of patients' evoked potentials. A cutoff of 2.5 standard deviations from the normal control value was used in discriminating normal from abnormal responses among patients. This cutoff would include 98% of the normal population, with an error probability of approximately .01 (Chiappa and Ropper, 1982). Patients were excused from Study III if they (1) had BAEP I-V interpeak latencies delayed more than 2.5 SD from normal values in both ears, or (2) if brainstem SEP components P12, N14 or P14 were delayed more than 2.5 SD from normal latency values after stimulation of both median nerves. In either case, the functional integrity of the brainstem would be open to question. In addition, patients were excluded if they had more than a 20 dBHL hearing loss in both ears at the 1000 and 2000 Hz frequencies employed in the CNV experiments (Study III).

Scoring. In order to perform correlational analyses between the neurosensory measures and the demographic data described in Study I, the neurosensory data were also rated on an ordinal scale. Because EP measurements (amplitude, latency) have a Gaussian distribution, judgement of normality is usually based on deviation from well-established "norms." However, brain damage may not attenuate and

lengthen the latency of these waveforms, thus changing their morphology. Responses can become so distorted that identification of individual waves is not possible, ruling out the use of standard measurement techniques (Lindsay et al., 1981). Several investigators (e.g. Greenberg et al., 1977a,b; Hall, Huang-Fu & Gennarelli, 1982; Rappaport et al. (1981a) have dealt with this problem by using a grading system to rank the responses as deviations from normal.

A similar method was used in the current study. A score of 0 was given to those waveforms in which the measured peak latencies were within 2.5 standard deviations of the normal control mean. A score of 1 was given to those waveforms in which the latency of one or more peaks was delayed more than 2.5 standard deviations from the normal mean. A score of 2 was given those waveforms in which normal latencies were obtained, but one or more peaks were absent. A score of 3 was given those waveforms which had both abnormal latencies and missing peaks. Thus, the more abnormal the waveform morphology, the higher the score.

Audiometric data were scored separately for each ear at the 1000 and 2000 Hz frequencies used in the subsequent CNV task. A hearing loss was considered abnormal if it was more than 20 dB SL (ISO 1964). An additive, ordinal-level scale was used, such that a score of 1 was added for every 10 dB beyond the 20 dB cutoff at 1000 and 2000 Hz. For example, if in one ear a patient had a 30 dB loss at 1000 Hz, and a 50 dB loss at 2000 Hz, he received a score of 4; i.e., a combined loss of 40 dB beyond the 20 dB cutoff. The other ear was scored separately. One patient withdrew from the study before this test.

could be administered, and one patient was excluded from this and the CNV test because of communication difficulties secondary to aphasia.

Results

BAEP and Audiogram Data

Normative data. Typical control waveforms are shown in Figure 3-1. Also included in the Figure are latency and amplitude values for men and women controls and their combined data. The BAEP revealed five prominent positive peaks. Of these, the peak and interpeak latencies of waves I and V were recorded as a measure of early auditory processing (peak I mean latency = 1.48 ms, SD = 0.14 ms; peak V mean latency = 5.50 ms, SD = 0.21 ms; mean I - V latency = 4.02 ms, SD = 0.23 ms). There were no significant sex differences in these data. All controls had normal audiograms.

----- Figure 3-1 about here -----

Results of Auditory Screening. Nineteen of the 20 tested patients had both normal BAEP I-V interpeak latencies and normal audiograms at 1000 and 2000 Hz in at least one ear. (Two patients had normal BAEPs but did not complete audiogram testing). These tests did detect significant bilateral hearing loss in 1 patient, and he was excluded from further participation. Results of the auditory screening are presented in Table 3-1.

----- Table 3-1 about here -----

Three patients had marginal BAEPs in their better ear. These patients had delays in peaks I, V, or both, but had normal interpeak latencies and normal audiograms at 1000 and 2000 Hz. Because the click stimulus used in the BAEP test is composed largely of high frequencies, delays in peak I often occur in cases of high frequency hearing loss. These 3 patients' audiograms were therefore reviewed. All had hearing losses of at least 30 dB above 2000 Hz. Because these high frequency hearing losses may have been responsible for the delay in peaks I and V, and because these patients had normal interpeak latencies and normal hearing at the tonal frequencies employed in the CNV task, they were included in later tests. Figure 3-2 shows BAEP data from 2 patients, one whose morphology is completely normal, and one who showed delays in Peaks I and V, but in whom a normal I-V IPL was obtained. This patient had a high frequency hearing loss in the tested ear.

----- Figure 3-2 about here -----

Nonparametric correlations (Kendall's tau) were performed between results from the auditory tests. Results from left and right audiograms were correlated, $\tau = .517$, $p < .01$, as were results from left and right BAEPs, $\tau = .420$, $p < .02$. BAEPs and audiograms were also significantly correlated, for both the left ($\tau = .495$, $p < .01$) and right ($\tau = .548$, $p < .01$) ears.

SEP data

Normative data. Typical control waveforms are presented in Figure 3-3. Associated mean latency data are also presented in the Figure. In the ipsilateral Erb's point to Fpz montage (trace 1 in the Figure), a small positivity about 8.6 ms after stimulation (P8; mean latency = 8.6 ms; SD = 0.9 ms) preceded a prominent negativity occurring about 10 ms after stimulation (N9; mean latency = 10.2 ms; SD = 1.0 ms).

----- Figure 3-3 about here -----

An electrode over the 7th cervical vertebra referenced to Fpz (trace 2) consistently recorded a negativity at about 14 ms (N14; mean latency = 13.8 ms; SD = 1.4 ms). A component of similar latency but reversed polarity (P14; mean latency = 14.3 ms; SD = 1.5 ms) was prominent in a far-field recording with a non-cephalic reference (contralateral cortex (C3 or C4) to contralateral Erb's point; trace 3 in Figure 3-3). In addition, an earlier positivity was seen in this third montage, about 2 ms before P14 (P12; mean latency = 12.1 ms; SD = 1.0 ms).

Cortical responses were best recorded from a contralateral cortex (C3 or C4) to Fpz montage (trace 4). Of these, the most consistent was an N20 - P22 complex (N20 mean latency = 19.5 ms; SD = 1.5 ms; P22 mean latency = 22.3 ms; SD = 1.5 ms). The appearance and latency of later responses was more variable, but included a negativity at about

32 ms (N30; mean latency = 32.3; $\underline{SD}$ = 3.9 ms) and a positivity around 40 ms (P40; mean latency = 41.4 ms; $\underline{SD}$ = 4.3 ms).

In order to control for presumed differences in the lengths of subjects' arm, a relative latency (from the brachial plexus negativity recorded over Erb's point) was calculated in addition to the latency from stimulus onset (absolute latency) for the somatosensory EPs. Control values for these relative latencies are also given in Figure 3-3. The sex difference between the latencies of the brachial plexus response were not significant. There were significant differences between the sexes on both absolute and relative measures of several later components.

Results of SEP screening are presented in Table 3-2. Of the 22 patients tested, all but one had bilaterally normal brainstem somatosensory evoked potentials (P12, N14, P14). A typical patient's normal SEP waveforms are illustrated in the upper portion of Figure 3-4. The one patient who did not have normal brainstem SEPs was also dysarthric due to injury to cranial nerves IX and X, and produced brainstem morphology of such quality that the responses could not be scored. This patient's SEP is shown in the bottom portion of Figure 3-4.

----- Table 3-2 and Figure 3-4 about here -----

In contrast to the normality of patients' brainstem SEP responses, 14 of the 22 patients had either unilateral (n = 8) or bilateral (n = 6) abnormalities in their cortical responses (N20 through P40). Two patients manifesting this pattern of responses are

shown in Figure 3-5. Patients with evidence of cortical SEP abnormalities were, however, included in the CNV task.

----- Figure 3-5 about here -----

Relationship of neurosensory results to demographic data. Non-parametric correlations (Kendall's tau) were performed between results from the neurosensory tests and patients' demographic data (age at injury, depth and duration of coma, PTA, and outcome). As shown in Table 3-3, none of the correlations reached significance at the $p < .01$ level. Evoked potential rating scores were also summed across modalities to give an "EP impairment index." A modest nonparametric correlation was found between duration of coma and the number of EP abnormalities (Kendall's tau = .340, $p = .017$). The strength of this relationship improved only slightly when audiometric data was included (tau = .357, $p = .013$).

----- Table 3-3 about here -----

Discussion

To establish the functional integrity of peripheral sensory and brainstem structures in patients, evoked potential testing was carried out in the auditory and somatosensory modalities. Controls matched with patients on age and sex provided normative data. Normative

responses recorded at St. Vincent Hospital were in excellent agreement with published values.

Brainstem auditory responses included five prominent peaks. The latency to peaks I, V, and their interpeak latency were taken as measures of auditory processing through the brainstem. These components are thought to represent responses from the cochlear nerve (peak I), and the region of the lateral lemniscus and inferior colliculus (peak V; Picton et al., 1981).

Somatosensory evoked potentials included nine components, ranging from peripheral nerve to cortex. This study concentrated on seven components recorded from four montages. Presumed generators of early responses include the distal portion of the brachial plexus (N9), the dorsal columns (P12), and the area of the medial lemniscus (N14, P14; Desmedt & Huy, 1984; Leuders, Lesser, Hahn, Little & Klem, 1983; Tsuji, Shibasaki, Kato, Kuroiwa & Shima, 1984; Wiederholt et al., 1982). Cortical responses were best recorded from a contralateral cortex to frontopolar montage. The most consistent of these was an N20-P22 complex, thought to reflect activity in and around primary somatosensory cortex. Although there is some controversy over the precise generators, N20 is thought to represent more posterior (ie., sensory) areas, while P22 is likely more frontal (ie., motor). Generators of later responses include the supplementary motor area (N30); and contralateral central regions (P45; Desmedt & Cheron, 1982). The specific sources of P45 are unknown (Desmedt & Bourguet, 1985).

Given the close correspondence between the current patient sample and larger patient samples (see Study I above), and the similarity of

these evoked potentials to data from other centers, it should be possible to generalize the obtained results to larger populations of head injured patients.

In general, few patients had significantly abnormal brainstem EPs. Although 7 patients had significant delays in the latency of BAEP peaks I, V, or both, all but 1 patient had either a better ear, or normal I-V interpeak latencies. A normal IPL was taken as evidence that the integrity of the CNS was not compromised at this level. In 3 patients, the latency delays were likely due to high frequency hearing loss. Only 1 patient was excluded from further testing on the basis of auditory system tests. Notably, this patient was excluded because of a severe bilateral hearing loss predating the head injury, not because of BAEP findings.

Early peripheral and brainstem components of the SEP also appeared to be normal in most patients. All but one patient displayed normal brainstem functioning in the somatosensory modality. This patient was rejected from further study.

On the other hand, tested patients were not without neurophysiological evidence of cerebral damage. Only 5 of the 22 patients showed no signs of abnormality on any of the evoked potential measures. Importantly, most patients (14 of 22) had evidence of cortical dysfunction in the somatosensory modality. A finding common to these latter patients was the slowing or absence of cortical responses P22, N30 and P40, thought to be generated in frontal motor and supplementary motor areas of cortex. Significant abnormalities among the late SEP responses occurred in the face of apparently normal brainstem functioning. These results tend to validate the concepts of

Ommaya and Gennarelli (1976), who have suggested that lower structures, including those in the brainstem, suffer last and least, even in cases of very severe head injury. These findings also suggest that even prolonged coma does not have a deleterious effect on the functional integrity of brainstem structures. This confirms observations of Karnaze et al. (1982), who found that normal brainstem responses could persist even in states of decerebrate coma.

No clear relationship was found between neurosensory abnormality and either injury severity or outcome, regardless of whether EP and audiometric scores were considered individually or together. This finding tends to support the claim of Rappaport et al. (1981b), who found a relationship between disability and EP abnormalities for initial stages of recovery, but not beyond 2 months. Patients in the present study were examined very late in the recovery process.

On the other hand, the lack of correspondence between clinical outcome and MEP results in the current study may be due to the restricted variability of outcome in the patient sample. Of the 22 patients tested in the present study, 20 were judged to have made satisfactory recoveries (good recovery or moderate disability on the Glasgow Outcome Scale, moderate or less disability on the Disability Rating Scale). According to reports from acute care centers, patients who go on to make satisfactory recoveries have normal MEPs, even in coma (Anderson, Bundlie & Rockswold, 1984; Greenberg et al., 1977a,b; Pfurtscheller et al., 1985). Thus, it was predicted that the less disabled patients in this study would have normal MEPs. In fact, this was the case. All patients who were rated as satisfactory recoveries had normal BAEP interpeak latencies in at least one ear, and

bilaterally normal brainstem SEPs. Of the 2 severely disabled patients, 1 showed signs of bilateral dysfunction in the somatosensory brainstem centers, while the other had normal brainstem responses in both modalities.

As a result of the screening procedures, two patients were excluded from testing in the CNV paradigm; one due to hearing loss, and one due to brainstem somatosensory deficits. In addition, the second severely disabled patient was excluded because severe expressive aphasia made it difficult to establish comprehension of task requirements. Finally, one parent objected to further participation of his son. Thus, from an initial sample of 22 patients screened on the neurosensory measures, 18 were deemed acceptable to continue with the later cognitive CNV task.

Figure 3-1. Typical control brainstem evoked potentials (BAEPs) following 80 dB nHL rarefaction click stimulation presented at a rate of 10/s. Normative and cutoff values for latencies to peak I, V, and their interpeak latency (IPL) are in the Table at the bottom of the Figure, with p scores for sex differences. The responses were recorded between the vertex and the lower ipsilateral mastoid. Clicks were presented monaurally and the responses obtained from either the left, or, as in this case, right ear. Two replications of 2048 stimuli each are superimposed; the bottom trace is the normalized sum, from which measurements were made. Stimulus artifact is visible within the first ms of click onset. The latency of BAEP peaks I and V of this typical control subject are within normal limits, as is the I-V IPL. In this and all other figures, negativity is indicated by an upward deflection.

Brainstem Auditory Evoked Potentials
Normative Data

	I lat.	V lat.	I-V lat.
Female			
M (SD)	1.42 (.08)	5.40 (.29)	4.06 (.29)
2.5 SD	1.22 - 1.62	4.68 - 6.13	3.34 - 4.79
Male			
M (SD)	1.53 (.17)	5.56 (.06)	4.01 (.18)
2.5 SD	1.10 - 1.96	5.41 - 5.71	3.56 - 4.46
Total			
M (SD)	1.48 (.14)	5.50 (.21)	4.04 (.23)
2.5 SD	1.13 - 1.83	4.98 - 6.03	3.46 - 4.62
p	.175	.318	.728

Figure 3-2. Patient BAEPs following stimulation of the left and right ears. In the upper tracings, a normal response is apparent in the left ear. All five positive peaks are well-defined, and the I-V IPL (4.12 ms) is within normal limits. In contrast, no response is apparent in the right ear. Behavioral audiometric examination revealed a profound hearing loss in this ear. Because of the normality of the left ear response, this patient (JM) was later tested in that ear in the CNV study. The lower tracings reveal delayed peaks I and V in both ears of a second patient (KD). However, the I-V IPLs were bilaterally normal, 3.92 ms on the left and 3.80 ms on the right. Audiometric testing revealed a bilateral high frequency hearing loss, secondary to bilateral rupture of the tympanum at the time of the head injury. Because this patient had normal thresholds for the 1 and 2 kHz frequencies used in the later CNV study, and had normal I-V IPLs (indicative of an intact auditory brainstem), he was allowed to participate in later CNV testing.

Figure 3-3. Typical control median nerve somatosensory evoked potential (SEP) with normative and cutoff values for absolute latencies (from stimulus onset; upper) and for relative latencies (from N9 brachial plexus response; lower). Probability values (p) are for sex differences. Responses in the figure were evoked by stimulation of the right median nerve by a 0.1 ms 5.5 mA constant current pulse, presented at 5/s. Two replications of 2048 stimuli each are superimposed. The four traces represent responses recorded from different electrode montages. In the top traces components P8 (at a latency of 7.9 ms in this subject) and N9 (9.4 ms) represent activation of the peripheral nerve at the brachial plexus, recorded from electrodes over ipsilateral Erb's point and at Fpz. The second traces were recorded between the 7th cervical vertebra and Fpz. The component N14 (12.9 ms) is probably generated by the medial lemniscus in the brainstem. The third traces were recorded from electrodes at C4 and Erb's point on the right shoulder. P12 (11.0 ms) likely represents activation of the dorsal column nuclei in the medulla, while P14 (12.9 ms), like N14, represents activation of the medial lemniscus. The bottom trace, recorded from electrodes at C4 and Fpz, shows several components. These are likely generated by thalamo-cortical radiations (N20; 18.4 ms), fronto-motor cortex (P22; 21.2 ms), and possibly the supplementary motor area (N30; 34.5 ms). The origins of P45 (43.7 ms) are not known, but probably derive from cortex contralateral to stimulation. Note the different calibration signals for each of the montages.

SEP Absolute Latencies

Female	P8	N9	N14	P12	P14	N20	P22	N30	P40
N (SD)	8.0 (.63)	9.6 (.8)	12.8 (.65)	11.4 (.8)	13.2 (.75)	18.3 (.9)	23.2 (.9)	31.13 (33.6)	38.7 (3.9)
2.5 SD	6.4 - 9.5	7.6 - 11.6	9.6 - 15.9	9.4 - 13.5	11.3 - 15.1	15.9 - 20.7	18.7 - 23.6	22.1 - 40.2	29.1 - 48.5
Male	P8	N9	N14	P12	P14	N20	P22	N30	P40
N (SD)	9.2 (.8)	10.9 (.8)	14.9 (1.2)	13.8 (.27)	15.4 (1.2)	20.6 (1.0)	23.42 (1.1)	32.9 (4.2)	43.2 (3.9)
2.5 SD	7.3 - 11.2	8.9 - 12.8	11.9 - 17.8	12.4 - 13.9	12.5 - 13.3	18.1 - 23.2	20.7 - 26.2	22.4 - 43.4	33.6 - 53.0
Total	P8	N9	N14	P12	P14	N20	P22	N30	P40
N (SD)	8.6 (.94)	10.2 (1.0)	13.8 (1.4)	12.1 (1.04)	14.3 (1.09)	19.46 (1.5)	22.29 (1.54)	32.3 (3.88)	41.4 (4.33)
2.5 SD	6.4 - 11.0	7.7 - 12.8	10.3 - 17.3	9.6 - 14.8	10.6 - 17.9	15.7 - 23.3	18.5 - 26.2	22.6 - 42.1	30.6 - 52.3
A	.013	.036	.004	.002	.003	.002	.004	.556	.112

SEP Relative Latencies (RE N9)

Female	P8	N9	N14	P12	P14	N20	P22	N30	P40
N (SD)	-1.6 (.19)	0.0	3.3 (.24)	1.9 (.88)	3.6 (.57)	8.7 (.45)	11.6 (.41)	21.6 (4.28)	29.3 (4.16)
2.5 SD	-2.1 - -1.1	-0.0	2.7 - 3.9	.06 - 4.1	.03 - 7.5	7.6 - 9.9	10.6 - 12.6	10.9 - 32.3	18.9 - 39.7
Male	P8	N9	N14	P12	P14	N20	P22	N30	P40
N (SD)	-1.6 (.13)	0.0	4.8 (.47)	2.3 (.9)	4.5 (.6)	9.7 (53)	12.5 (54.1)	22.0 (4.00)	32.3 (3.65)
2.5 SD	-1.96 - -1.35	0.0	2.8 - 5.15	0.15 - 4.25	2.95 - 6.1	8.4 - 11.06	11.2 - 13.85	12.46 - 31.95	23.2 - 41.45
Total	P8	N9	N14	P12	P14	N20	P22	N30	P40
N (SD)	-1.6 (.16)	0.0	3.6 (.32)	1.9 (.84)	4.07 (.74)	9.2 (.78)	12.1 (.67)	21.9 (3.8)	31.1 (3.97)
2.5 SD	-2.02 - -1.2	0.0	2.35 - 4.9	0.14 - 4.06	2.25 - 5.9	7.46 - 11.0	10.4 - 13.75	12.3 - 31.4	21.2 - 41.0
A	.528	.008	.701	.026	.006	.007	.008	.248	

Figure 3-4. Patient SEPs indicating normal and equivocal brainstem components. In the upper portion, a normal response to right median nerve stimulation at 19 mA is apparent. All components are well-defined and within normal limits. In the lower portion, a patient (GK) revealed a normal peripheral response (P9 and N11), indicating the median nerve was effectively stimulated. However, the dorsal column (P12) and brainstem (N13, P13) responses are of dubious quality. Stimulation of the left median nerve (not shown) revealed a similar morphology. Nevertheless, later cortical components N20 and P24 are normal, suggesting these are generated via a different pathway than the earlier brainstem components. Although this patient was not included in the results of the CNV experiment, he did participate in a case study. His performance did not attain criterion levels.

Patient (normal SEP)

R median n
(19 mA)

EP2-Fpz

CV7-Fpz

C3-EP1

C3-Fpz

R median n
(8 mA)

Patient (?brainstem)

EP2-Fpz

CV7-Fpz

C3-EP1

C3-Fpz

Figure 3-5. Patient SEPs indicating unusual or absent cortical responses. The patient in the upper half of the figure manifests a completely normal SEP in the first three traces. In the lower traces N20 and P24 are also apparent, suggesting functioning of the primary cortex. Later N30 and P45 peaks were not obvious. The patient in the lower half of the figure revealed a complete absence of any cortical response, although earlier brainstem and peripheral responses are within normal limits. Both patients were included in the later CNV study because subcortical components appeared normal.

Patient (abnormal cortical)

R median n
(10 mA)

EP2-Fpz

CV7-Fpz

C3-EP1

C3-Fpz

Patient (abnormal cortical)

L median n
(17 mA)

EP1-Fpz

CV7-Fpz

C4-EP2

C4-Fpz

Table 3-1

Results of Auditory Screening for 22 Patients

Patient	Right Ear						Left Ear					
	BAEP			Audiogram			BAEP			Audiogram		
	I	V	I-V	1kHz	2kHz	>2kHz	I	V	I-V	1kHz	2kHz	>2kHz
BB						*		*				*
JB	*	*				*				*	*	*
CC ¹				*	*	*	*	*	*	*	*	*
PC												
KD	*	*				*	*	*				*
LD												
BD ²				NT	NT	NT	NT	NT	NT	NT	NT	NT
PD						*						*
OE												
BG												
JH												
GK ²												
RL												
BL												
SM		*					NT	NT	NT		*	*
MM ²	*	*		NT	NT	NT				NT	NT	NT
HM						*						*
JM	*	*	*	*	*	*						
GM							NT	NT	NT			
GP						*						
LS												
GW						*						*

Note. * = > 2.5 SD latency delay or > 30 dBSL hearing loss.

NT = Not Tested.

1 Patient excluded due to hearing loss.

2 Patient did not complete study.

Table 3-2

Results of Somatosensory Evoked Potential Screening for 22 Patients

Patient	Right Median Nerve							Left Median Nerve						
	Brainstem SEP			Cortical				Brainstem SEP			Cortical SEP			
	P12	N14	P14	N20	P22	N30	P40	P12	N14	P14	N20	P22	N30	P40
BB														
JB							X							
CC ²					R						R			
PC					R									
KD														
LD														
BD ²					R									
PD	NT	NT	NT	NT	NT	NT	NT							
OE					R	X	X				X		X	
BG					R									
JH														
GK ¹	X		X					A						
RL														
BL					R									
SM					R		X						X	
MM ²														
HM														
JM						X	X				X		X	
GM					R									
GP													X	
LS					R						R			
GW					B						R			

Note. X = Component absent.

A = > 2.5 SD absolute latency delay (from stimulus onset).

R = > 2.5 SD relative latency delay (from brachial plexus).

B = > 2.5 SD latency delay for absolute and relative measures.

NT = Not Tested.

1 Patient excluded due to SEP finding.

2 Patient did not complete study.

Table 3-3

Correlations between Patients' Neurosensory and Demographic Data

	Right Audio- gram	Right BAEP ¹	Left Audio- gram	Left BAEP	Right SEP ² (abs) ³	Right SEP (rel) ⁴	Left SEP (abs)	Left SEP (rel)
Age at Injury	.299 (20) .058	-.026 (22) .442	-.118 (20) .260	-.023 (22) .447	-.173 (22) .160	.129 (22) .225	-.168 (22) .175	-.158 (22) .184
Glasgow Coma Scale	-.158 (20) .229	-.188 (22) .173	-.180 (20) .490	-.363 (22) .032	.021 (22) .457	-.124 (22) .258	-.068 (22) .369	.059 (22) .383
Duration of Coma	.012 (20) .475	.224 (22) .107	.282 (20) .065	.306 (22) .042	.194 (22) .469	.213 (22) .402	.314 (22) .043	.146 (22) .212
Post- Traumatic Amnesia	.000 (18) .500	.131 (19) .257	.414 (18) .021	.323 (19) .053	.495 (19) .159	.095 (19) .310	.193 (19) .169	-.009 (19) .482
Time Since Injury	.132 (20) .244	.227 (22) .101	.119 (20) .259	.058 (22) .370	.017 (22) .460	-.015 (22) .464	.232 (22) .099	.104 (22) .278
Glasgow Outcome Scale	.100 (20) .326	.180 (22) .190	.099 (20) .322	-.084 (22) .338	.107 (22) .297	.197 (22) .157	.185 (22) .186	.121 (22) .276
Disability Rating Scale	.263 (20) .104	.118 (22) .272	.155 (20) .221	.026 (22) .445	.092 (22) .314	.099 (22) .296	.087 (22) .328	.021 (22) .457

 : Corr. coeffic. :
 Key: : (N) :
 : Probability :

* Kendall's tau rank-order correlation $p < .01$

1 Brainstem Auditory Evoked Potential.

2 Somatosensory Evoked Potential.

3 Absolute latency (from stimulus onset).

4 Relative latency (from brachial plexus).

Chapter 4

Study IIIInformation Processing

Available evidence indicates that the CNV is modulated by CNS pathology produced by head injury, with more aberrant CNVs associated with more diffuse and severe damage. However, it is not clear whether diffuse pathology causes a general attenuation of the CNV, as reported by McCallum and Cummins (1973) and Rizzo et al. (1978), or an exaggeration and disinhibition of these responses (Curry, 1980).

Typical of early ERP work (Pritchard, 1981), the three studies relied on the correlation between the manipulation of a directly observable variable, in this case CNS pathology, and resultant changes in the CNV. Although this design has a long tradition in experimental psychology, in the reviewed cases the dependent measure - the CNV - was not used as a metric for drawing inferences about CNS pathology, but rather head injury was used to learn about the CNV. In other words, it seems the CNV has been the phenomenon of interest, not head injury. As a consequence, the only null hypothesis tested was that the CNV would not be affected by head injury. This is clearly not the case; head injury does affect the CNV.

Equally evident is the real slowing of reaction time after closed head injury, as reviewed in Chapter 1. Although only McCallum and Cummins (1973) presented RT data gathered in an ERP paradigm, the numerous reports of slowed RT after CHI suggest the finding is ubiquitous. What remains unclear is the cause of the slowing.

Under- and Overprocessing. The CNV data obtained to date suggest two possible origins of the behavioral slowing. On the one hand, Curry's (1980) results indicate that the slowing might be due to a failure to ignore redundant information. Recall that the most common finding among patients in his modified Go/No-Go CNV task was a large CNV after both "Go" and "Stop" warning stimuli. Thus, the paradigm elicited an inappropriately large CNV following a WS which indicated the imperative stimulus (IS) could be ignored. Although the data were not analyzed in terms of O- and E-waves, this abnormally large CNV was most prominent in frontal regions, during the early portion of the waveform. This fits well with the description of the O-wave given by Loveless (1979) and Loveless and Sanford (1974).

This result suggests patients may have been overprocessing information, and needlessly preparing to respond. Rather than use the information in WS to decide whether or not to respond, and simply waiting for IS to make that response, Curry's patients seemed to make inefficient use of their limited resources. Importantly, this overprocessing occurred in the face of accurate performance of the task, suggesting a dissociation of behavioral and neurophysiological measures. Thus, while the CNV indicated at least a needless initial preparation to respond, performance was behaviorally correct (i.e., no response was actually made). Overprocessing might be at the root of what Levin et al. (1979a) referred to as a "filtering problem" among their patients, manifested in an inability to disregard irrelevant or uninformative material, and attend to the task at hand. This hypothesis would also serve to explain the easy fatigability so often reported among CHI patients.

On the other hand, results presented by McCallum and Cummins (1973) and Rizzo et al. (1978) suggest that patients may be underprocessing information. These authors reported reduced and attenuated CNVs as their major finding among head injury patients. Evidence from the CNV literature suggests that this symmetrical, widespread attenuation, affecting both early and late portions of the CNV complex, represents not only a failure to orient to warning stimuli, but also a failure to prepare to respond to imperative stimuli. Without adequate preparation, responses can be accurate, but will be slow.

van Zomeren (1981) has suggested that these results may reflect deficits in phasic arousal. These are rapid changes in alertness, dependent on a subject's interests and intentions. Phasic alertness may be contrasted with the slow and involuntary changes of tonic alertness, such as the diurnal rhythm. While slow changes in the overall tone of alertness are better measured by continuous reaction time performance and vigilance tasks, phasic levels of alertness are best measured through forewarned RT tasks, such as the Go/No-Go CNV paradigm. None of the three studies cited above adequately controlled for possible changes in phasic arousal. Perhaps the easiest means to test the role of phasic arousal is through replication of the condition: the entire procedure is repeated at least once to determine if the results are subject to change with time.

Alternative explanations. Although these hypotheses have a certain amount of intuitive appeal, and may serve to help isolate the nature of the slowing after CHI, the CNV results described above might be due to phenomena which are psychologically far less complex. The

most obvious of these is eye movements. Although the experience of the investigators would indicate that they were aware of the possible confound represented by EOG contamination of the EEG, trials contaminated by EOG were not rejected, but either subtracted (McCallum & Cummins, 1973; Rizzo et al., 1978), or simply monitored (Curry, 1980).

It is also possible that the results were due to primary sensory deficits, such as hearing impairment. Because none of the studies reported giving patients even cursory sensory examinations, presumed deficits in information processing could be due to the degradation of information at a very peripheral level.

Also, descriptions of patients participating in these studies suggest that neurosurgical cases were involved. As a result, EEG activity recorded near burr holes or skull flaps may not have been attenuated by the order of magnitude attributed to intact brain coverings (Walter, 1964; unpublished personal observations). Again, the experience of the investigators would indicate that they were aware of this possible problem, but none made mention of precautions taken to avoid it. Alternative methods of controlling for skull defects may account for some of the differences in variability reported by McCallum and Cummins (1973) and Rizzo et al. (1978). The first study reported the standard deviations of patients' peak CNV were nearly twice the normal value. On the other hand, Rizzo et al. (1978) presented variability bars for patients which were smaller than those of controls.

It could also be argued that the attenuated patient CNV was due to anxiety associated with the demands of a relatively complex task.

Knott (1972) found that anxious subjects exposed to a stressful experimental situation had small CNVs. He argued that the attenuating effect of anxiety on the CNV (see also McCallum & Walters, 1968) is due to an elevation in the DC level of the baseline EEG, against which the CNV is measured. If this were true, the apparent reduction in the CNV would actually be a ceiling effect, against which the CNV could not rise. This possibility was evaluated in the present study by the manipulation of task demands. Finally, all three studies treated the CNV as a unitary phenomenon, a concept now widely recognized as inaccurate. One would expect evidence of overprocessing to be most prominent in the frontal O-wave, while underprocessing would be most obvious in the central and parietal E-wave. Unfortunately, the recording parameters used in these studies preclude the detailed analysis of the CNVs' component structure.

Rationale. In order to distinguish between the underprocessing and overprocessing hypotheses described above, an elaborate CNV-type paradigm was employed using survivors of severe head injury who had gone on to make satisfactory recoveries in the years since their injury. It was hypothesized that underprocessing would be manifested by low-amplitude CNVs in all conditions, including WS-Go trials. This would be particularly apparent in the later E-wave of the CNV, which is largest at central scalp sites. Inadequate readiness to respond could in turn explain slowed RT. Overprocessing would be manifested in an inappropriately large CNV following WS-Stop trials, perhaps particularly apparent in the early frontal O-wave. Such a finding would suggest a needless preparation to respond to an irrelevant S2. In this case, slowed RTs might best be explained by "information

overload" and resultant fatigue. Figure 4-1 depicts results predicted by the under- and over- processing hypotheses.

----- Figure 4-1 about here -----

Method

Subjects

Patients. Only those patients who had passed the neurosensory screening tests described in Study II were asked to participate in this study. Of the 20 patients who passed the screening, one was excluded because severe expressive aphasia made testing very difficult. Another patient's parent objected to further participation, and withdrew his son. Eighteen patients (13 males, 5 females) were eventually tested in this study. All were classified by independent raters as having made good recoveries or being moderately disabled. Further descriptions of this group are given in Chapters 2 and 3.

Controls. Patients who participated in event-related potential and behavioral testing were individually matched with control subjects on the basis of age, education, sex and handedness. The mean control age was 25.2 years (SD = 6.0 years), while the mean age of patients was 25.4 years (SD = 6.6 years). Controls averaged 14.4 years of educations (SD = 2.5 years), whereas patients averaged 13.8 years (SD = 2.7 years). These differences were not significant.

Both patient and control subjects were paid \$20.00 for participating in this study. Informed consent (Appendix F) was obtained before the session. Total testing time was approximately 3 hours, although for some subjects it was extended to about 4 hours (explained later).

Apparatus and Procedure

Subjects were tested in a sound-attenuating chamber, listening to stimuli presented to their better ear through Telephonics TDH-39 headphones. Stimuli consisted of 1000 Hz (LO) and 2000 Hz (HI) 55 ms tone pips, presented under computer control at 80 dB SPL(A). Each trial consisted of a pair of tones: a warning stimulus (WS), and 1400 ms later, an imperative stimulus (IS). The interval between trials was 5 s. Eighty trials were presented for a total duration of about 10 minutes. Subjects were instructed to keep eye movements and blinking to a minimum. To obviate eye movements, subjects were asked to fixate a point mounted approximately one meter distant at eye level.

Two different CNV paradigms were run. In the first, four combinations of WS/IS tones were presented: HI/HI, HI/LO, LO/HI, and LO/LO, each with equal probability ($p = .25$). Order of presentation was randomized. One of the four stimulus pairs was designated as a target, randomized across subjects. The subject's task was to respond as soon as possible to the second tone in the target pair, and to not respond to any of the other three pairs of stimuli. Thus, one WS (WS-Go) informed the subject that a response might be necessary following the IS, while the alternative WS (WS-Stop) informed the subject that no response would be required, regardless of the pitch of

the IS. This task, which was similar to the modified Go/NoGo CNV task used by Curry (1980), is hereafter referred to as the 4-stimulus task.

As an example, suppose the combination "HI/LO" was designated as a target pair. On a random 25% of the 80 trials, a 2000 Hz stimulus (WS-Go) was followed 1400 ms later by a 1000 Hz imperative stimulus to which the subject was to respond (IS-Go). On another 25% of the trials, the subject was presented with a HI/HI combination; in these cases the subject was to refrain from responding following the second stimulus (IS-NoGo). Thus, in half the trials the same WS (WS-Go) could be followed by either a Go (LO tone) or a NoGo (HI tone) IS. Because the subject could ~~not~~ predict whether a Go or a NoGo IS would occur, a CNV would be expected to develop in both cases. On the other 50% of the trials, the LO tone served as the WS. This WS (WS-Stop) informed the subject that no response would be required, regardless of the pitch of the IS. Thus, following WS-Stop, a CNV would not be expected to develop, since the information required for successful completion of the task was contained in the WS.

Because it could be argued that the patient CNV might be abnormal due to factors such as task complexity or anxiety associated with the task (rather than under- or overprocessing per se), a second, simpler task was deemed necessary. The task was similar to the 4-stimulus task, except that the first signal was always a WS-Go signal; the pitch of the imperative stimulus determined whether the subject was to respond. For half of the subjects, a LO tone served as a WS, while a HI tone served as a WS for the other half. Half the subjects were told to respond following the LO IS, the other half following the HI IS. Since only two WS/IS pairs (Go/Go and Go/NoGo) were presented

(again, at random and with equal .50 probability), this paradigm is referred to as the 2-stimulus task. It was similar to the traditional Go/NoGo CNV paradigm used by McCallum and Cummins (1973) and Rizzo et al. (1978).

To guard against practice and order effects, the 2- and 4-stimulus tasks were presented in counterbalanced order. To insure replicability, and investigate patterns of phasic arousal, all 36 subjects completed the 2- and 4-stimulus paradigms twice. Nine patients and 9 controls performed both tasks 3 times.

Recording parameters. The EEG was recorded from the scalp at Fz, Cz and Pz by Beckman silver/silver-chloride non-polarizable electrodes, affixed to abraded skin with collodion-impregnated gauze and adhesive collars. The low mastoid contralateral to the stimulus served as the reference. Eye movements (EOGs) were recorded by electrodes placed on the infra- and supra-orbital ridges of the right eye. Abrasion of the skin was required to overcome possible contamination caused by electrodermal responses (EDRs; Picton & Hillyard, 1972). Since EDRs are also slow negative DC shifts, they may contaminate EEG recordings of true intracerebral slow activity. The inter-electrode impedance (measured at 30 Hz) for all EEG electrodes was always less than 1 kOhm, while that for the EOG electrodes was always less than 2 kohms. EEG and EOG activity was amplified (25,000 X) by a Nihon Kohden electroencephalograph. The high frequency filter was set at 25 Hz. The time constant was modified to be 2.4 s. In addition to paper write-outs of EEG and EOG, this device also recorded stimulus delivery and subject responses.

Electrophysiologic, stimulus and response data were interfaced from the EEG machine to the A/D converter of a Cromemco Z-80 micro-computer for on-line analysis (Makasare, Campbell, Stelmack & Knight, 1985). EEG and EOG activity from each of the stimulus combinations was averaged on-line at a resolution of 8 ms per point for 2400 ms, beginning 400 ms prior to the first stimulus. An artifact rejection protocol was used such that trials in which EOG or Fz signals were larger than ± 75 μ V were not included in the average. The averages were stored on diskette for later off-line scoring and plotting. Reaction times were recorded by a Racal Universal Counter (model 835) at a resolution of 1 ms.

Behavioral Data Analysis

4-Stimulus condition. In this paradigm, a total of 80 stimulus pairs were presented, of which a random 25% were targets requiring a button-press response. Numerous measures of performance were obtained, including hit rate to targets, the number of false alarms, and several measures of reaction time (RT), including the fastest RT, the mean, the median, and both range and standard deviation measures of variability. To obtain the measures, the statistic in question (e.g., median) was determined for each subject in each replication. With the exception of the fastest RT, these statistics were based on about 20 reaction times per replication per subject. Repeated measures comparisons (BMDP2V) were then performed on the data, with one between factor (patient vs control) and up to three within levels (replication). For all comparisons, the level of significance was set at $p < .01$.

2-Stimulus condition. A total of 80 stimulus pairs were presented in this paradigm also, of which a random 50% were targets requiring a response. The same measures of performance were taken as in the 4-stimulus condition. In this task between-group comparisons were based on an average of 40 responses per replication for every subject. As before, the level of significance was set at $p < .01$ for all between-group comparisons.

Physiological Data Analysis

For statistical purposes, the CNV waveform at each electrode site was divided into six 96 ms epochs, beginning 224 ms after the first stimulus (the WS). The time between epochs was 120 ms. The resulting epochs were as follows: (1) 224 - 320 ms, (2) 440 - 536 ms, (3) 656 - 752 ms, (4) 872 - 968 ms, (5) 1088 - 1184 ms, and (6) 1304 - 1400 ms. As shown in Figure 4-2, epoch 1 coincided with the resolution of the N1-P2 complex following the WS, and marked the beginning of the O-wave of the CNV complex. Epoch 2 was associated with the peak amplitude of the O-wave, and Epoch 3 with its resolution. Epochs 4, 5, and 6 were taken as measures of the E-wave of the CNV. For each electrode location, a computer scoring technique determined a prestimulus baseline as the average of activity in the 400 ms prior to the onset of the WS. The same program also determined the average of the EEG activity for each of the 6 different CNV epochs for each electrode site, relative to the prestimulus baseline at that electrode site.

----- Figure 4-2 about here -----

Statistical Analyses

In the 4-stimulus condition, a 4-way ANOVA was applied to the data, with one between factor (patient vs control) and repeated measures on 3 factors: WS (Go vs Stop), IS (GO vs NoGo), and replication (up to 3). In the case of the 2-stimulus condition, a 3-way ANOVA was run on the data (WS was not manipulated). Separate ANOVAs were run for each electrode site and each of the six epochs (i.e., 18 different analyses for both the 2- and 4-stimulus conditions). The six epochs were not considered as a repeated measure factor since principle components analysis (McCallum & Curry, 1981; Sanquist et al., 1981) has shown the O- and E-waves to be statistically independent. Because of the possibility of chance findings, the level of significance was set quite high ($p < .01$). Pearson product-moment correlations (SPSS, 1983) were performed between CNV and RT measures.

To determine if group signs of over- and underprocessing could be attributed to individual subjects, subjects were categorized into "normal" and "abnormal" groups on the basis of behavioral and physiological results. Normative values were established for each of the four WS-Stop trials (two imperative stimuli X two replications) in the 4-stimulus task, using control data from the 3rd epoch at the frontal electrode. Data were considered within normal limits if they fell within two standard deviations of the control mean. Thus, there were four cutoff points. Subjects with one or more CNVs larger than two standard deviations above the control mean were classified as

overprocessors. Similarly, underprocessors were identified as those subjects whose central WS-Go CNV in epoch 6 was more than two standard deviations smaller than the control mean in the same task. The four cutoff values used were derived from control CNVs in the four WS-Go trials (two imperative stimuli X two replications).

Over- and underprocessors were also identified through data from the 2-stimulus condition. Overprocessors were defined as those subjects with CNVs larger than two standard deviations above control data for the 3rd epoch at the frontal electrode. Underprocessors were identified as subjects with epoch 6 central CNVs smaller than two standard deviations below the control mean. Again, four cutoffs were used for each classification: two imperative stimuli X two replications.

Categorizations were also made on the basis of RT. Slow subjects were identified using cutoff scores from control data for median and fastest RTs. Four cutoffs were used, corresponding to the 4 trials requiring a behavioral response (2 replications of the 4-stimulus condition, 2 replications of the 2-stimulus condition). Slow subjects were defined as those with any RT measure slower than two standard deviations above the control value.

Chi-square analyses were performed to test the apportionment of subjects into groups on the basis of these data. Patients classified as under- and overprocessors were also compared on demographic data, using t-tests.

Results

Behavioral Measures

4-Stimulus condition. The behavioral results are summarized in Table 4-1. Because there was generally no effect of replication, values presented in this Table are collapsed across two replications ($N = 18$ patients, 18 controls) or three replications ($N = 9$ patients and 9 controls).

----- Table 4-1 about here -----

Collapsed across two replications, the hit rates for patients (.98) and controls (.99) were very high. The difference between groups was not significant. Very similar results were obtained when data from three replications were used (patients = .97, controls = .99). However, because there were no misses (and hence was no variability) among the controls in one of the replications, the slight difference in hit rate was significant. The number of false alarms in each replication was also recorded. There were small, non-significant differences between patients and controls.

The fastest reaction time in each replication was identified for each subject, using data from the two or three replications. The mean fastest RT among patients was significantly slower than that of controls for two replications (261 ms vs 217 ms). Patient - control differences approached significance ($p < .05$) for three replications (240 ms vs 209 ms). There was a slight trend for patients to become

slower with increasing replications. The fastest RTs for patients and controls are plotted in the top portion of Figure 4-3.

----- Figure 4-3 about here -----

There were also large differences between patients and controls on mean RT. These differences, on average more than 100 ms, were significant over all replications. There was a tendency for patients to become slower in later replications, although this effect did not reach significance. Patient and control mean RT are presented in the top portion of Figure 4-4.

----- Figure 4-4 about here -----

The standard deviation of each subject's RT was also obtained for every replication. These deviations were then subjected to an ANOVA. A significant interaction was found between group and replication when data from two replications were used. Whereas patients tended to become more variable with additional replications, control variability remained more or less the same. In addition, there were significant group differences, with patient standard deviations averaging nearly three times that of controls. These findings are shown in the bottom portion of Figure 4-3.

Similar results were obtained when the range of individual subjects' RT was used, with significantly less variability among controls, regardless of the number of replications.

An examination of the RT distributions revealed a positive skewness for both groups. Because there was significantly more variability on individual trials for the patients than the controls, use of the mean RT data may be inappropriate. As an alternative, the median RT is largely unaffected by extreme scores or skewness. As shown in the Table, controls were approximately 100 ms faster than patients on this measure ($p < .01$). Median RTs for patients and controls in two and three replications are shown in the bottom portion of Figure 4-4.

2-Stimulus condition. Behavioral results from the 2-stimulus condition are presented in Table 4-2. Because no effects of replication were found, data presented in the Table are collapsed across two replications ($N = 18$ patients, 18 controls) or three replications ($N = 8$ patients and 8 controls).

----- Table 4-2 about here -----

Performance levels were very high for both patients and controls in this task. However, because of extremely low variability in the control data, significant differences were obtained between groups on hit rate.

There were no differences between the groups on the average number of false alarms, regardless of the number of replications. Thus, although this paradigm required that subjects always be prepared to respond, there was less than one false alarm for every 40 nontarget stimuli.

On the other hand, there were large differences in all measures of RT. Collapsed across two replications, the average fastest RT among patients was approximately 50 ms slower than that of controls, a significant difference. As shown in the top portion of Figure 4-5, there was a trend for patients to become slower, and controls to become faster, in the second replication, although this interaction did not reach significance. When the number of replications was increased to three, the overall 33 ms difference only approached significance.

----- Figures 4-5, and 4-6 about here -----

Large group differences were also found on mean RT. As shown in the top portion of Figure 4-6, there was a trend for patients to become slower, and controls faster, with additional replications. Measures of response variability also showed large group differences. Both standard deviation and range measures showed significant differences between patients and controls, with patient RTs approximately twice as variable as that of controls. In addition, patients showed a clear trend to become more variable with additional replications, while control variability remained roughly constant. Standard deviation for patients and controls are shown for all three replications in the bottom portion of Figure 4-5. Median RTs were also compared, to reduce the influence of extremely long reaction times. As in the 4-stimulus case, the median RT of patients was about 100 ms slower than that of controls. These data are presented in the bottom portion of Figure 4-6.

Although large patient - control differences were obtained on measures of RT in both the 2- and 4-stimulus conditions, the ANOVA assumption of homogeneity of variance was frequently violated; that is, critical values of Hartley's (1940, 1950) F_{max} were exceeded. However, when equal sample sizes are used, as in the present case, the F test is robust with respect to violations of this assumption (Cochran, 1947). Moreover, when the variances are very heterogeneous, the principle effect is to increase the level at which results can be considered significant (Rogan & Keselman, 1977). Although the significance level was set at $p < .01$ for all RT tests, patient - control differences in RT remained significant at $p < .005$.

CNV Measures

4-Stimulus condition. Figure 4-7 depicts the superimposed Grand Averages of controls and patients in the four stimulus conditions. Figures 4-8 and 4-9 show the superimposed tracings of all patients and controls in the WS-Go and WS-NoGo trials, respectively. Control tracings in these Figures show the characteristic morphology and scalp distribution of the CNV. Following the N1-P2 complex immediately after the WS, the O-wave of the CNV developed. Maximal between 350 and 700 ms after the WS, the O-wave was largest at Fz and smallest at Pz, in many cases falling below baseline at that electrode site. In the middle portion of the recording epoch, the CNV showed different patterns, depending on WS. Following WS-Stop, the O-wave resolved to baseline at all electrode sites. Following WS-Go, the O-wave recorded at Fz began to level off. At central and parietal sites, the O-wave gave way to a large E-wave. This later component continued to gain in

amplitude at central and parietal sites until the onset of the IS. At all sites, a second N1-P2 complex developed after the IS, with a large parietal P3 appearing in WS-Go trials.

----- Figures 4-7, 4-8 and 4-9 about here -----

For each of the six epochs and for each electrode site, no interactions or main effects involving replication were found. Similarly, there were no significant interactions or main effects involving IS (Go vs NoGo). In all but the first epoch, there were several significant group differences, including main effects of WS and a group X WS interaction. These results are presented in Table 4-3.

----- Table 4-3 about here -----

Figure 4-10 shows the mean CNV amplitude for WS-Go and WS-Stop at each of the six epochs, for each electrode site. Simple main effects testing of group differences for each WS are presented in Table 4-4.

----- Figure 4-10 and Table 4-4 about here -----

At the Fz electrode (upper portion of Figure 4-10), there were no significant group differences at any epoch following WS-Go. However, following WS-Stop, the patient O-wave was significantly larger than that of controls during Epoch 3 (656-752 ms), and almost significantly larger ($p < .05$) following epoch 4.

At the Cz site (middle portion of Figure 4-10), the control E-wave (epochs 4, 5 and 6; 872 - 1400 ms) was significantly larger than that of patients following WS-Go. However, following WS-Stop, the patient O-wave tended to be larger than that of controls. Consistent with a similar finding at Fz, this difference tended towards significance in epoch 2 (440-536 ms; $p < .05$).

As shown in the bottom portion of Figure 4-10, the control E-wave in epochs 5 and 6 at the Pz electrode was significantly larger than patients' following WS-Go. The control - patient difference in epoch 4 tended towards significance ($p < .05$). There were no significant group differences following WS-Stop at the parietal site.

Another trend visible in Figure 4-10 was that patients seemed less able than controls to modulate their CNV. Simple main effects testing was therefore carried out to compare the effects of WS within each group. Thus, control data for WS-Go and WS-Stop were compared, and differences in patients' WS-Go and WS-Stop data were examined. Results are presented in Table 4-5. For controls, WS-Go CNVs became very much larger than WS-Stop CNVs in the second epoch at frontal and central electrodes. The difference was nearly as large at the parietal site. At all electrode sites, the WS-Go - WS-Stop difference remained large ($p < .01$) from epoch 2 until the onset of IS. In contrast, the WS-Go / WS-Stop difference took longer to reach significance. Moreover, the differences were much smaller than for controls.

----- Table 4-5 about here -----

CNV - RT correlations. Pearson product-moment correlations were performed between the mean CNV amplitude in the last epoch prior to the IS and the five RT measures (fastest, mean, median, range, and standard deviation) associated with those trials. Of the 30 RT- CNV correlations (5 RT measures X 3 electrode sites X 2 replications), none of the control relationships were significant at $p < .01$. One modest correlation ($r = -.51$; $p < .05$) was found between frontal CNV and the fastest RT in one replication. Similar results were obtained among patients. Only two modest correlations ($.01 < p < .05$) were found between patient CNVs and RTs. These correlations involved the Cz CNV and both mean RT ($r = .42$) and median RTs ($r = .43$) in a single replication.

2-Stimulus condition. Figure 4-11 depicts the superimposed Grand Averages of controls and patients in the two stimulus conditions. Figure 4-12 shows the superimposed tracings of 18 patients and 18 controls in the same paradigm. Control tracings show the characteristic morphology and scalp distribution of the 2-stimulus CNV. The CNV morphology was very similar to that obtained in the WS-Go conditions of the 4-stimulus paradigm. An O- wave was maximal at frontal and central sites early in the recording, and a later E-wave was largest at central and parietal locations.

----- Figures 4-11 and 4-12 about here -----

Analysis of the 2-stimulus CNV involved ANOVAs for the data from the six epochs at each electrode site. Results are summarized in

Table 4-6. There were no main effects or interactions involving replication or IS. However, as shown in the Table and in Figure 4-13, there were significant group differences for some of the epochs.

----- Table 4-6 and Figure 4-13 about here -----

At the frontal electrode (top portion of Figure 4-13), patients developed a large O-wave (epoch 2) which remained elevated until the IS. Controls also showed an early O-wave in epoch 2, but, in contrast to patients, this component fell back towards baseline before the onset of the later E-wave in epoch 4. The difference between the patients' prolonged O-wave and the diminution of the control O-wave was significant in epoch 3. No other group differences were obtained at the frontal site.

There was also a large difference between controls and patients at the central electrode (middle portion of Figure). Although patient and control CNVs were virtually identical in epochs 1 and 2, the patient CNV tended to asymptote at that point. In contrast, the control CNV continued to increase in amplitude from epochs 3 through 6. The control-patient difference reached significance just prior to the IS, in epoch 6.

At the parietal electrode (bottom portion of Figure), patient CNVs were larger than controls' in the temporal domain of the O-wave (epochs 1, 2 and 3). However, the control CNV increased at a greater rate than patients across later epochs, and was actually larger than patients' during the period of the E-wave (epochs 5 and 6). None of

the group differences at this electrode site were significant at $p < .01$.

CNV - RT correlations. Pearson product-moment correlations were performed on the mean CNV amplitude recorded from each electrode in epoch 6 (just prior to the IS) and the five RT measures associated with those trials. None of the control measures were correlated. Among patients, several significant correlations ($p < .01$) were obtained, all in the second replication. The epoch 6 CNV recorded at Cz was significantly associated with the fastest RT ($r = .60$), the mean RT ($r = .64$), the RT standard deviation ($r = .59$), the range of RT ($r = .57$), and the median RT ($r = .64$).

2- vs. 4-Stimulus Conditions

RT measures. Within-group comparisons were made of reaction time measures obtained in the 2- and 4-stimulus conditions. There were no significant differences between 2- and 4-stimulus RTs for either group.

CNV measures. Comparison of control WS-Go CNVs in the 2- and 4-stimulus conditions revealed significant amplitude differences at all electrode sites. Compared to CNVs obtained in the 4-stimulus condition, the 2-stimulus control CNV was considerably smaller. At the Fz electrode (upper left portion of Figure 4-14), this difference was significant during the early portion of the CNV [$F(1,17) > 14.8$, $p < .01$ for epochs 2, 3, 4, and 5]. Significant differences were also found in the CNV recorded at the Cz site (middle portion of left panel). These differences were significant for nearly all parts of the CNV, $F(1,17) > 15.0$, $p < .01$ for epochs 2, 3, 4, 5 and 6. At the

Pz site (bottom left of Figure) the difference between conditions was significant for epochs 3 through 6, $F(1,17) > 14.4$, $p < .01$.

----- Figure 4-14 about here -----

In contrast, patient CNVs recorded in the 2-stimulus condition were not significantly different from those recorded in the 4-stimulus condition. The similarity of waveforms recorded from patients in the two conditions is shown in the right-hand panel of Figure 4-14.

Individual Differences

Because the obtained results were group differences, it was not readily apparent whether a given patient was prone to underprocessing, overprocessing, or both. Further investigations were therefore carried out to determine whether individual subjects could be classified as normal processors, underprocessors, overprocessors, or both.

For the 4-stimulus condition, a small central CNV in the 6th epoch of WS-Go trials was taken as evidence of underprocessing, while overprocessing was defined as an unusually large frontal O-wave in the 3rd epoch of WS-Stop trials.

On the basis of the criteria derived from the 4-stimulus condition, 8 patients and 1 control were classified as underprocessors, and 4 patients and 2 controls were classified as overprocessors. In addition, 2 patients showed evidence of both under- and overprocessing. Only 4 patients were found to have completely normal CNV amplitudes values. In all, 14 patients and 3

controls were found to have CNVs beyond these cutoffs. This assignment was statistically significant, corrected Chi square (1, $N = 36$) = 11.15, $p < .001$. The correspondence between anomalous CNVs and membership in the patient group was highly significant, Kendall's tau = .612, $p = .0001$.

Categorization was also performed using the control data from the 2-stimulus condition. A small 6th epoch Gz E-wave indicated underprocessing, whereas a large 3rd epoch Fz O-wave suggested overprocessing. In this analysis 4 patients were classified as underprocessors, and 1 control and 5 patients were classified as overprocessors. Because these criteria identified an additional patient as having an anomalous CNV, cutoffs from both conditions were used in a final tabulation. In the resulting assignment, 15 of 18 patients were classified as having abnormal CNVs, and 15 of 18 controls were classified as having normal CNVs. The corresponding hit and miss rates were 83.3 and 16.7 percent, respectively. These results were highly significant, Chi square (1, $N = 36$) = 13.44, $p < .001$. Overall, only 3 patients had "normal" CNVs; 8 patients were classified as underprocessors, 5 were classified as overprocessors, and 2 additional patients showed evidence of both types of anomaly in their CNVs.

To learn more about the makeup of these two apparently distinct groups of patients, t -tests were performed on their demographic data, including time since injury. The two patients who both under- and overprocessed were excluded from this analysis to decrease the amount of shared variance in the under- and overprocessing groups. The only statistically significant difference was a modest finding on the

Glasgow Coma Scale [$t(11) = -2.38, p < .05$], with over-processors having somewhat deeper comas than underprocessors (4.4 vs 5.5). To see if time since injury (TSI) had any bearing on under- or over-processing, tested patients were divided into three groups, based on this variable. Short TSI was defined as 0 to 2.7 years ($n = 7, M = 1 \text{ year, } 9 \text{ months}$); middle TSI was 2.7 to 4 years ($n = 6, M = 3 \text{ years, } 4 \text{ months}$); long TSI was greater than 4 years ($n = 5, M = 4 \text{ years, } 9 \text{ months}$). There was no relationship between the time since injury and the presence of under- or overprocessing. In fact, each of the three groups had virtually the same proportion of CNV anomalies as the total sample.

Reaction times were evaluated to differentiate between, on the one hand, patients from controls, and, on the other, underprocessors from overprocessors. Subjects were considered significantly slow if they had one or more median or fast RTs more than 2 standard deviations slower than the control average. Using these criteria, 15 patients and 4 controls were classified as having significantly slow RTs. Thus, this test served nearly as well as the CNV test in discriminating patients from controls, Chi square (1, $N = 36$) = 11.15, $p < .001$. To determine if RT measures could discriminate between over- and underprocessors, the 8 patients classified as underprocessors were compared to the 5 patients classified as overprocessors on the basis of reaction time. No differences were obtained on any RT measure. In fact, nearly identical values were obtained for each group.

Reaction time was not completely redundant with CNV scoring, however. Crosstabulations were performed to identify those subjects

who had abnormal values in either the 4-stimulus or the 2-stimulus CNV tests and slow RTs. While those patients who had abnormal CNVs typically also had slow RTs, this was not the case among controls. Whereas 14 of 18 patients had both abnormal CNVs and slow RTs, none of the controls did. This classification was highly significant, Chi square (1, $N = 36$) = 19.75, $p < .0000$.

To see if localized cerebral lesions had any bearing on these results, reviews were made of patients' SEP results (from study II), as well as the CT scan and neurosurgical reports from the acute care centers. No clear relationship was found between over- or under-processing and SEP abnormalities. Neither was there an obvious association between neurosurgical or CT scan signs of cerebral hematoma or contusion and CNV anomalies. As shown in Table 4-7, normal responses occurred in spite of CT scan evidence of frontal hematoma and delayed cortical SEPs (patient BL). On the other hand, signs of both under- and overprocessing could occur without evidence of localized cerebral lesions (patients JB, LD, HM).

----- Table 4-7 about here -----

Statistical comparisons between the demographic data of the patients who were consistently classified as having normal CNVs and normal reaction times and the other patients revealed no significant differences.

Discussion

Performance data from the 2- and 4-stimulus conditions indicate that both patients and controls performed these relatively complex tasks well, with little change in accuracy over as many as six 10-minute sessions. On the other hand, while patients were consistently accurate, there was an apparent cost in RT, as they were significantly slower or more variable than controls on every RT measure. Although the ANOVA assumption of homogeneity of variance appeared to be violated, the robust nature of F and the very large differences between groups indicates that these differences in RT are meaningful.

Patients tended to become slower and more variable in their RT with additional replications, suggesting a fatigue effect. Median RT showed a less pronounced slowing trend over replications than did mean data, indicating that patient mean RTs were influenced by a few extremely slow responses. Median RTs may therefore more accurately reflect overall performance speed in this group. Median and fastest RTs proved to be very good discriminators of group membership, correctly classifying 15 of 18 patients (83%) and 14 of 18 controls (78%). This pattern of accurate but slow performance replicates a number of other studies of head injury, including those of Miller (1970) and van Zomeren (1981).

This study was designed to do more than simply replicate previous work, however. In fact, given the literature on performance after head injury, it was largely assumed that patients would be slow. The rationale of the present study was to provide insight into why patients might be slow.

The CNV data gathered in this study provide rather clear support for the notion that the behavioral slowing so common after head injury may be due to one of two factors, underprocessing or overprocessing.

In both 2- and 4-stimulus conditions, patients and controls developed large, frontally-maximum O-waves following a WS that informed them that a response might be required following IS. For both groups, these responses were most pronounced in Epochs 2 and 3. However, as the EEG sweep continued, large differences appeared between patient and control CNVs in both 2- and 4-stimulus conditions. Whereas the control CNV continued a steady negative shift in epochs 2 through 6, the slope of the patient CNV appeared to decrease soon after the second epoch. These patient - control differences in the WS-Go E-wave reached statistical significance at all electrode sites. Importantly, this pattern was not apparent in all patients, but seemed restricted to 10 of the 18. Given evidence that the E-wave represents a sign of response preparation, these patients failed to develop normal patterns of expectancy for the impending response requirements. Thus, it seems they underprocessed the warning stimuli in WS-Go trials. The slow reaction times obtained in these trials would appear to be an unavoidable consequence of this lack of an adequate preparation to take action.

Seven patients showed a second type of CNV anomaly in WS-Stop trials. Both patients and controls developed prominent O-waves in these trials, best visualized in epoch 2 at the frontal site. However, while the control O-wave rapidly diminished, the somewhat larger patient O-wave was very slow to resolve. Thus, while both patient and control CNVs eventually reached the same amplitude, some

patients were substantially slower in the resolution of their O-wave. It seems that these patients devoted an inappropriate amount of time and energy to the processing of redundant and task-irrelevant information; they overprocessed the warning stimuli in WS-Stop trials. The delay in the return of patients' O-wave to baseline might reflect a slowness in their decision making, with those patients taking longer to process the relevant information contained in WS-Stop. Behavioral measures were not apparent in these trials, indicating that patients were able to understand and comply with instructions. However, the fatigue presumably produced by such overvigilance took its toll. Patient RTs became slower and more variable with continued replications, perhaps as a consequence of this inefficient use of attentional resources.

Evidence of overprocessing was also obtained in the 2-stimulus condition, which required that subjects always be prepared to make a behavioral response. Whereas both patients and controls developed a frontally maximal O-wave after the WS, the control EEG fell back towards baseline before the onset of the later E-wave. In contrast, the patient EEG did not resolve, but remained elevated until the IS. It is believed that controls came to realize that all WS presented in the 2-stimulus task were Go signals, and that these stimuli held no predictive value for determining response preparedness. Controls may therefore have regarded these signals only as time markers, and as a consequence generated rather small O-waves. This strategy did not involve a cost in RT, as there were no differences between 2- and 4-stimulus reaction times for controls. In contrast, patient O-waves recorded in the 2-stimulus condition were indistinguishable from those

recorded in the 4-stimulus condition. This finding indicates that patients exerted needless effort in their processing of the rather limited information in the 2-stimulus WS-Go signal. This over-processing was of dubious value, as patient CNVs were still significantly smaller, and RTs significantly slower, than those of controls.

The concepts of over- and underprocessing are robust in their ability to account for the data. Although the RT tests were more easily administered, scored and interpreted than the EEG tests, and were more economical in terms of both time and equipment, they did not provide the information available in the CNV results. Over- and underprocessors had nearly identical RTs on all measures. Thus, while RT accurately identified those persons who had sustained head injuries, it did not readily suggest the nature of the behavioral slowing. The CNV results not only distinguished between patients and controls more accurately than RT tests, it identified two distinct groups of slow patients. The CNV data also seem to account for slow RTs; patients who were not slow did not have aberrant CNVs, and only 1 patient who had slow RTs did not also have an abnormal CNV. Finally, only 2 patients showed signs of both under and overprocessing, suggesting that these are phenomena are largely independent.

Are other interpretations of the CNV data possible? In the introduction to this chapter, several problems were noted in other studies of head injury which utilized the CNV. One of the most serious was other investigators' treatment of eye movement artifact. The problem was overcome in the present study by simply rejecting those trials in which large eye movements and blinks occurred. Grand

averages of subject and group data demonstrate the utility of this technique.

Previous studies were also criticized for their lack of control in recording from neurosurgical cases. Because of the prevalence of burr holes and bone flaps amongst the head injured, it is not practical to exclude these cases. However, care must be exercised in recording EEG from these patients, as an electrode placed too near a skull defect can produce misleading results when compared to recordings from intact sites (H. Jasper, personal communication, May, 1984). In the present case, extreme care was taken to identify the location of skull defects, and record from a suitable distance. The superimposition of patients' data (Figures 4-8, 4-9 and 4-12) indicates that evidence of overprocessing was not a recording artifact.

It is also unlikely that the results obtained from patients in this study were due to sensory deficits. In addition to audiometric screening, all patients underwent extensive evoked potential testing before participating. Due to differences in the neuroanatomical distribution of the auditory and somatosensory systems, the gathering of auditory and somatosensory EPs from each patient enabled a substantial portion of the primary sensory CNS to be evaluated (Newlon & Greenberg, 1983). Two patients were excluded from this study because of suspected sensory deficits.

Previous studies have also failed to demonstrate that the changes in the CNV subsequent to head injury were not due to subject anxiety or task complexity. Knott (1972) and McCallum and Walters (1968) have shown that anxiety has an attenuating effect on the CNV, due to an

elevation of the baseline EEG. In the present study, task complexity was manipulated to modulate CNV amplitude. The control CNV was significantly different between the two conditions, indicating that the manipulation was effective. While there was no difference between 2- and 4-stimulus CNVs among patients, the results do not coincide with an anxiety hypothesis. The effect of anxiety is to attenuate the CNV, whereas the manipulation of task complexity had the effect of making the control CNV larger, not smaller as would be expected from the anxiety hypothesis. Thus, it seems unlikely that the attenuation of the patient CNV in the 4-stimulus condition was due to the task or experimental setting.

The CNV is also affected by attention, phasic arousal and motivation (McCallum, 1969; Tecce, 1972; Tecce & Scheff, 1969). In the present study, up to three replications of the same condition were recorded. The CNV did not change significantly over time in either group. It is also unlikely that patients' results are due to motivation, given the consistently high hit rates. In fact, most patients volunteered that they were glad to participate.

There was a suggestion in the data that patients were less able to modulate their CNV than controls. For example, in the 4-stimulus condition, there were large differences between Go and Stop control CNVs, but much smaller differences in the patient data. Similarly, there were large differences in the control data taken from the 2- and 4-stimulus conditions, while the patient data in the two conditions was nearly indistinguishable. These results may be due to the statistical treatment of the patients as one homogeneous group, rather than the more accurate representation of three independent subgroups

of normal processors, overprocessors, and underprocessors. However, it has been suggested that head injury results in a reduced ability to differentially respond to the environment (Brooks, 1984a,b; Lezak, 1978; Oddy, 1984). These deficits are usually ascribed to lesions of the frontal lobes. The behavioral consequences of frontal lobe damage are complex (Stuss and Benson, 1982), but include losses of self-control, foresight, and spontaneity. Given the prevalence of frontal lobe lesions after head injury in general (Gurdjian & Gurdjian, 1976), and especially in the present sample (see Table 4-7), this hypothesis may account for differences between under- and overprocessors.

It is now recognized that personality changes are related to the portion of the frontal lobes involved (Hecaen & Albert, 1975). Damage to the lateral convexity often results in a lack of drive, apathy, inability to plan ahead, and an air of indifference. Blumer and Benson (1975) reported that patients with lateral convexity lesions appeared depressed, but lacked clinical signs of depression such as sense of failure, loss of appetite, and self-hate. Rather than being preoccupied with morbid thoughts, as is common in depression, these patients had an empty indifference to their state. These authors termed such patients "pseudo-depressed".

On the other hand, persons who sustained damage to the orbital portion of the frontal lobes tended to have problems with impulse control and self-restraint. Changes were manifested in boastfulness, shallow affect, aggressiveness, sexually disinhibited or inappropriate behavior, and a generally self-indulgent attitude. Paranoid or

grandiose ideation sometimes occurred. Blumer and Benson (1975) referred to these patients as "pseudo-psychopathic".

These apparently distinct syndromes of "pseudo-depression" and "pseudo-psychopathy" correspond rather well with the notions of under- and overprocessing proposed in the present study. Only 2 patients showed signs of both under- and overprocessing, indicating that these are phenomena are also largely independent, as would be expected if they were induced by different lesion locations. Unfortunately, the CT scan and neurosurgical reports do not provide enough detail to make a direct association between, say, underprocessing and dorsolateral lesions, or overprocessing and orbital lesions. Neither were extensive clinical descriptions of personality made. It must also be remembered that not all personality changes after CHI can be attributed to the frontal lesions. Both orbital and dorsolateral surfaces have extensive connections with the temporal lobe, particularly limbic areas. Thus, damage to the amygdala or septum can also result in disinhibited, pseudo-psychopathic behavior (Valenstein & Heilman, 1979). Similarly, the dorsolateral convexity projects to the cingulate and reticular activating system of the temporal lobes. A lesion of the circuit can induce changes in phasic arousal, including emotional blunting and hypoarousal (Carpenter, 1976).

Perhaps even more importantly, the role of premorbid personality in these changes is difficult to determine, and admittedly was not extensively examined in the present study. Although Lezak (1983) notes that personality characteristics are "not so much changed as exaggerated by brain injury", Stuss and Benson (1982) suggest that the dominant role of premorbid personality is "more difficult to prove

than to surmise." Citing several case histories, Blumer and Benson (1975) argued that some personality changes could not be predicted from premorbid characteristics. Brooks and McKinlay (1983) concluded that personality changes were a function of several factors, including the location of damage, premorbid personality characteristics, and the social milieu or family organization dominant during the patient's recovery.

These authors also found that the likelihood of personality change increased with the severity of the injury. However, the severity of the injury did not predict the extent or nature of the personality change. Whereas the personality changes found after focal lacerations to portions of the frontal and temporal lobe may be rather sharply delineated or take certain forms, the personality and emotional changes after severe diffuse injury are somewhat more pervasive. Clearly, the relationship between under- and overprocessing, personality changes, and localized prefrontal lesions awaits further study.

Figure 4-1. Hypothesized consequences of under- and overprocessing in modified Go/NoGo CNV paradigm. In this task the warning stimulus (WS) indicates whether a second stimulus might require a response (WS-Go), or can be ignored (WS-Stop). While a normal control CNV (solid line) shows a large difference between WS-Go and WS-Stop conditions it is hypothesized that underprocessing (dotted line, top) would be manifest by low amplitude CNV in the WS-Go condition, indicating inadequate readiness to respond. Overprocessing (dotted line, bottom) would be associated with abnormally large CNV following WS-Stop, suggesting inability to ignore task- irrelevant information.

HYPOTHESES

UNDERPROCESSING: low amplitude CNV after WS-Go reflects inadequate preparation to respond to the imperative stimulus.

OVERPROCESSING: Inappropriately large CNV after WS-Stop reflects needless processing of redundant information.

Figure 4-2. Measurement of CNV waveforms. For statistical purposes, the CNV recorded from each electrode site was divided into six 96 ms epochs, beginning 224 ms after the first stimulus, indicated by the arrow at time 0. The time between epochs was 120 ms. Epoch 1 (224-320 ms) coincided with the resolution of the N1-P2 complex following the WS, and marked the beginning of the O-wave of the CNV complex. Epoch 2 was associated with the peak amplitude of the O-wave, and epoch 3 with its resolution in WS-Stop trials. In WS-Go trials, such as depicted here, epoch 3 marked a transition between the O- and E-waves. Epochs 4 (872 - 968 ms), 5 (1088 - 1184 ms), and 6 (1304 - 1400 ms) were taken as measures of the E-wave. The end of epoch 6 coincided with the presentation of the imperative stimulus (second arrow), 1.4 s after WS. A computer scoring technique determined the average of the EEG activity for each of these six epochs, relative to prestimulus baseline activity in the 400 ms preceding WS.

CNV Measurement

Figure 4-3. Behavioral measures from patients and controls in 4-stimulus condition: fastest RT (top) and RT standard deviations (bottom). Fastest RT measures were determined by first identifying each subject's fastest RT in each replication. An average fastest RT was then calculated for each group for each replication. Patients' fastest RT was significantly slower than controls' fastest RT. Moreover, patients tended to get slower with increasing replications, whereas controls maintained the same response speed across replications. Standard deviation measures (bottom) were determined by calculating the standard deviation of RT for each subject in each replication, and then computing the group average at each replication. Each subject made about 20 responses in each replication. Patients were significantly more variable than controls. In addition, patients tended to increase in variability with increasing trials, while control variability remained relatively constant. The interaction between patients and controls at replications 1 and 2 was significant.

Fastest Reaction Time 4 Stimulus Condition

Reaction Time Standard Deviations 4 Stimulus Condition

Figure 4-4. Behavioral measures from patients and controls in 4-stimulus condition: mean RT (top) and median RT (bottom). Both statistics were calculated by the same technique as the mean standard deviations in Figure 4-3. Each subject made about 20 responses in each replication. Patients were significantly slower than controls on both mean and median RT across all replications. Patients' mean RT tended to get slower with increasing replications. This effect is likely due to a few very long reaction times in later replications, as the trend is not as obvious in patients' median data. On both measures controls became slightly faster across replications.

Mean Reaction Time 4 Stimulus Condition

Median Reaction Time 4 Stimulus Condition

Figure 4-5. Behavioral measures from patients and controls in 2-stimulus condition: fastest RT (top) and RT standard deviations (bottom). Fastest RT measures were determined as in Figure 4-3. Patients' fastest RT was significantly slower than controls' fastest RT. Moreover, patients tended to get slower with increasing replications, whereas controls maintained the same response speed across replications. Standard deviation measures (bottom) were calculated as in Figure 4-3, with each subject making about 40 responses in each replication. Patients were significantly more variable than controls. Furthermore, patients tended to increase in variability with increasing trials, while control variability remained relatively constant.

Fastest Reaction Time 2 Stimulus Condition

Reaction Time Standard Deviations 2 Stimulus Condition

Figure 4-6. Behavioral measures from patients and controls in 2-stimulus condition: mean RT (top) and median RT (bottom). Both statistics were calculated as in Figures 4-3. Each subject made about 40 responses in each replication. Patients were about 100 ms slower than controls on both mean and median RT, a significant difference. In addition, patients' mean RT tended to get slower with increasing replications. This effect is less pronounced in patients' median RT data, suggesting it may have been due to a few trials with extremely long RTs. On both measures controls became slightly faster across replications.

Mean Reaction Time 2 Stimulus Condition

Median Reaction Time 2 Stimulus Condition

Figure 4-7. Superimposed grand averages of behavioral and physiological data for controls (thick lines) and patients (thin lines) in 4-stimulus condition. Each vertical panel represents one of the four stimulus conditions. WS-Go informed the subject that a behavioral response might be required following the IS. A response was required after IS-Go (far left-hand panel) but not after IS-NoGo (second panel from left). Because subjects could not predict whether IS-Go or IS-NoGo would occur, a CNV was expected to develop prior to both. Reaction time histograms are given for IS-Go trials. In WS-Stop trials (right-hand panels), the first stimulus informed the subject that no behavioral response would be required, regardless of the IS. Thus, no CNV was expected to develop. The EEG was recorded from midline frontal (Fz), central (Cz) and parietal (Pz) electrodes for 2400 ms, beginning 400 ms prior to WS-Go (stimulus onset indicated by ordinate). Trials containing EEG or eye movement (EOG) artifacts were rejected automatically. Tick marks on vertical axes indicate 2.5uV (negative up). Horizontal tick marks indicate 80 ms. Control tracings show the characteristic morphology and scalp distribution of the CNV. Following the N1-P2 complex immediately after the WS, the O-wave of the CNV developed. The O-wave was largest at Fz and smallest at Pz. In the middle portion of the recording epoch, the CNV showed different patterns, depending on WS. In WS-Go trials (two left-hand panels), the O-wave recorded at Fz began to level off. At central and parietal sites, the O-wave gave way to a large E-wave. This later component continued to gain in amplitude at central and parietal sites until the onset of the IS. There was a large control E-wave in these trials. In contrast, the patient E-wave was smaller. Following WS-Stop (right hand panels), the control O-wave resolved to baseline at all electrode sites. The patient O-wave was somewhat larger and took longer to return to baseline. At all sites, a second N1-P2 complex developed after the IS, with a large parietal P3 appearing in WS-Go trials.

Figure 4-8. Superimposition of behavioral and physiological data for individual controls and patients in 4-stimulus condition: WS-Go trials. WS-Go informed the subject that a behavioral response might be required following the IS. A response was required after IS-Go (two left-hand panels) but not after IS-NoGo (two right-hand panels). Because subjects could not predict whether IS-Go or IS-NoGo would occur, a CNV should have developed prior to both. Reaction time histograms are given for IS-Go trials. The EEG was recorded and displayed as in Figure 4-7, except that tick marks on vertical axes indicate 4uV (negative up). Each individual tracing is the average of two replications. All controls developed large O- and E-waves in these trials. In contrast, several patients developed CNVs which were very much attenuated, particularly during the E-wave component just prior to IS.

4-Stimulus Condition: WS-GO, IS-GO
18 CONTROLS

4-Stimulus Condition: WS-GO, IS-NOGO
18 PATIENTS

Figure 4-9. Superimposition of behavioral and physiological data for individual controls and patients in 4-stimulus condition: WS-Stop trials. WS-Stop informed the subject that no behavioral response would be required, regardless of the IS. Thus, no CNV was expected to develop. The EEG was recorded as in Figure 4-7, and is displayed as in Figure 4-8. There is little evidence of a CNV among controls. In contrast, several patients have inordinately large O-waves at frontal and central electrode sites.

4 Stimulus Condition: WS-STOP, IS-NOGO
18 CONTROLS

4-Stimulus Condition: WS-STOP, IS-GO
18 PATIENTS

Figure 4-10. Mean control and patient CNV measurements after WS-Go and WS-Stop in 4-stimulus condition. Data for 18 controls (solid lines) and 18 patients (dashed lines) were derived from six CNV epochs, collapsed across replication and 1st as described in Figure 4-2. Following WS-Go, the control E-wave was significantly larger than that of patients at Cz (epochs 4, 5 and 6) and at Pz (epochs 5 and 6). Following WS-Stop, the control O-wave was significantly smaller than patients' at Fz (epoch 3). In addition, the control data showed very large differences between WS-Go and WS-Stop conditions at all electrodes, whereas the patient data from the two conditions separated more slowly and to a lesser extent.

Mean CNV Following WS-GO and WS-STOP
4-Stimulus Condition

Figure 4-11. Superimposed grand averages of behavioral and physiological data for controls (thick lines) and patients (thin lines) in 2-stimulus condition. Each vertical panel represents one of the two stimulus conditions. The WS informed the subject that a behavioral response might be required following the IS. A response was required after IS-Go (left-hand panel) but not after IS-NoGo (right panel). Because subjects could not predict whether IS-Go or IS-NoGo would occur, a CNV was expected to develop prior to both. Reaction time histograms are given for IS-Go trials. The EEG was recorded and displayed as in Figure 4-7. Control tracings show the characteristic morphology and scalp distribution of the CNV in this condition. Following the N1-P2 complex immediately after the WS, the O-wave of the CNV developed. The patient O-wave was larger than controls'. In the middle portion of the recording epoch, the control O-wave recorded at Fz began to level off. At central and parietal sites, the O-wave gave way to a large E-wave. This later component continued to gain in amplitude at central and parietal sites until the onset of the IS. There was a large control E-wave in these trials. In contrast, the patient E-wave is smaller. At all sites, a second N1-P2 complex developed after the IS, with a large parietal P3.

2-Stimulus Condition
WS-GO, IS-GO WS-GO, IS-NOGO
CONTROLS: — PATIENTS: —

Figure 4-12. Superimposition of behavioral and physiological data for individual

controls and patients in 2-stimulus condition. The WS informed the subject that a behavioral response might be required following the IS. A response was required after IS-Go (two left-hand panels) but not after IS-NoGo (two right-hand panels). Because subjects could not predict whether IS-Go or IS-NoGo would occur, a CNV should have developed prior to both. Reaction time histograms are given for IS-Go trials. The EEG was recorded and displayed as in Figure 4-7, except that tick marks on vertical axes indicate 4uV (negative up). Each individual tracing is the average of two replications.

Controls developed large E-waves in these trials, but rather small O-waves. In contrast, several patients developed relatively large O-waves, and rather small E-waves.

2-Stimulus Condition: WS-GO, IS-GO 18 PATIENTS 18 CONTROLS

Figure 4-13. Mean control and patient CNV measurements in the 2-stimulus condition. Data for 18 controls (solid lines) and 18 patients (dashed lines) were derived from six CNV epochs, collapsed across replication and IS as in Figure 4-10. At the frontal electrode (top panel), patients developed a large O-wave that persisted until the IS, whereas the control O-wave at this electrode site fell back towards baseline before the onset of the E-wave. The difference between groups was significant in epoch 3 at this electrode. At the central electrode (middle panel), the patient CNV seemed to asymptote after the 2nd epoch, whereas the control CNV continued to increase. The group difference reached significance in epoch 6, just before the IS. No significant between-group differences were found at the Pz electrode site.

Mean CNV Following WS-GO
2-Stimulus Condition

Figure 4-14. Mean control and patient CNV measurements after WS-Go in 2- and 4-stimulus conditions. Data for 18 controls (left panels) and 18 patients (right panels) were derived from six CNV epochs, collapsed across replication and IS as described in Figure 4-10. For controls, the 2-stimulus CNV was significantly smaller than that obtained in the 4-stimulus condition, at all electrode sites. The 2- and 4-stimulus patient CNVs were very similar at all electrodes.

Table 4-1

Results of Analysis of Variance for
Patient and Control Performance Measures
4-Stimulus Condition

	Two Replications		Three Replications	
	<u>M</u>	(<u>SD</u>) <u>F</u> (1,34)	<u>M</u>	(<u>SD</u>) <u>F</u> (1,16)
<u>Hit Rate</u> (proportion)				
Patients	.98	(.05)	.97	(.06)
Controls	.99	(.01) 3.97	.99	(.00) 9.5*
<u>False Alarms</u> (number)				
Patients	.25	(.27)	.63	(1.4)
Controls	.22	(.55) .04	.22	(.44) 1.27
<u>Fastest RT</u> (ms)				
Patients	261	(64)	240	(36)
Controls	217	(27) 9.03*	209	(30) 6.48
<u>Mean RT</u> (ms)				
Patients	443	(204)	416	(92)
Controls	297	(42) 9.87*	300	(59) 15.42*
<u>Median RT</u> (ms)				
Patients	384	(133)	359	(64)
Controls	284	(42) 10.5*	282	(49) 13.22*
<u>RT SD</u> (ms)				
Patients	193	(202)	199	(126)
Controls	62	(37) 8.75*	76	(58) 10.91*
<u>RT Range</u> (ms)				
Patients	731	(732)	821	(576)
Controls	264	(198) 9.44*	290	(224) 10.69*

* $p < .01$

Table 4-2
Results of Analysis of Variance for
Patient and Control Performance Measures
2-Stimulus Condition

	Two Replications		Three Replications	
	<u>M</u>	(<u>SD</u>) <u>F</u> (1,34)	<u>M</u>	(<u>SD</u>) <u>F</u> (1,14)
<u>Hit Rate</u> (proportion)				
Patients	.98	(.19)	.98	(.19)
Controls	1.00	(.03) 7.46*	.99	(.03) 12.48*
<u>False Alarms</u> (number)				
Patients	.30	(.56)	.37	(.69)
Controls	.14	(.35) 1.71	.29	(.35) .16
<u>Fastest RT</u> (ms)				
Patients	243	(63)	221	(38)
Controls	196	(22) 10.76*	188	(22) 6.24
<u>Mean RT</u> (ms)				
Patients	425	(132)	417	(108)
Controls	289	(35) 20.77*	285	(47) 11.67*
<u>Median RT</u> (ms)				
Patients	396	(117)	379	(95)
Controls	275	(36) 20.56*	270	(43) 9.72*
<u>RT SD</u> (ms)				
Patients	146	(84)	166	(102)
Controls	70	(27) 15.88*	74	(30) 8.94*
<u>RT Range</u> (ms)				
Patients	683	(295)	783	(538)
Controls	358	(181) 13.08*	377	(193) 6.29

* $p < .01$

Table 4-3

Results of Overall Analysis of Variance for
Each CNV Epoch in 4-Stimulus Condition¹

Source	Epoch					
	1	2	3	4	5	6
	F(1,34)	F(1,34)	F(1,34)	F(1,34)	F(1,34)	F(1,34)
<u>Fz Electrode</u>						
Group	.26	.67	2.48	.42	.16	1.26
WS	.54	22.16*	69.70*	88.71*	105.92*	109.48*
Group X WS	.60	5.01	8.60*	6.46	3.29	3.28
<u>Cz Electrode</u>						
Group	.93	.19	.00	2.22	6.60*	8.91*
WS	.05	26.30*	52.26*	67.21*	115.18*	118.85*
Group X WS	1.02	8.80*	6.75*	6.64*	5.35	7.50*
<u>Pz Electrode</u>						
Group	1.06	1.55	.02	1.58	5.04	9.85*
WS	1.12	7.81*	29.64*	73.75*	116.44*	139.63*
Group X WS	.15	5.49	5.37	8.87*	5.39	6.32

1. Collapsed across IS and replication.

* $p < .01$

3 3

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Table 4-4

Results of Comparisons of Patient vs Control CNVs
for Each CNV Epoch in 4-Stimulus Condition

	Epoch					
	1	2	3	4	5	6
<u>Fz Electrode</u>						
WS-GO						
Controls	-3.77	-8.95	-9.10	-9.11	-10.24	-11.49
Patients	-2.72	-9.11	-9.45	-8.16	-8.75	-9.09
F(1,34)	NT	NT	NT	0.74	1.65	2.66
WS-STOP						
Controls	-2.87	-5.63	-3.08	-2.10	-2.54	-2.95
Patients	-2.70	-7.93	-6.56	-4.13	-3.36	-3.07
F(1,34)	NT	2.30	8.03**	4.53*	NT	NT
<u>Cz Electrode</u>						
WS-GO						
Controls	-1.91	-7.96	-9.71	-11.88	-14.51	-16.67
Patients	-0.26	-6.48	-7.58	-8.13	-10.31	-10.99
F(1,34)	NT	0.86	2.36	8.10**	8.67**	10.39**
WS-STOP						
Controls	-1.12	-2.43	-1.73	-1.53	-2.46	-3.13
Patients	-0.66	-5.00	-3.82	-2.73	-2.53	-2.89
F(1,34)	NT	4.15*	3.65	.92	NT	NT
<u>Pz Electrode</u>						
WS-GO						
Controls	2.79	-0.28	-3.36	-6.81	-9.10	-10.45
Patients	1.65	-0.53	-1.94	-4.24	-6.35	-7.32
F(1,34)	NT	0.04	1.36	6.99*	8.59**	12.63**
WS-STOP						
Controls	2.49	2.52	1.01	-0.24	-1.37	-1.99
Patients	1.00	-0.29	-0.18	-1.05	-1.36	-1.83
F(1,34)	NT	3.92	1.36	0.98	NT	NT

NT Not Tested

* $p < .05$

** $p < .01$

Table 4-5

Results of Within-Group Comparisons of WS-GO vs WS-STOP
for Each CNV Epoch in 4-Stimulus Condition

	Epoch					
	1	2	3	4	5	6
<u>Fz Electrode</u>						
Controls						
WS-GO	-3.77	-8.95	-9.10	-9.11	-10.24	-11.49
WS-STOP	-2.87	-5.63	-3.08	-2.10	-2.54	-2.95
F(1,17)	NT	35.48***	182.92***	152.94***	164.01***	147.00***
Patients						
WS-GO	-2.72	-9.11	-9.45	-8.16	-8.75	-9.09
WS-STOP	-2.70	-7.93	-6.56	-4.13	-3.36	-3.07
F(1,17)	NT	2.31	8.86**	15.43**	23.14***	25.16***
<u>Cz Electrode</u>						
Controls						
WS-GO	-1.91	-7.96	-9.71	-11.88	-14.51	-16.67
WS-STOP	-1.12	-2.43	-1.73	-1.53	-2.46	-3.13
F(1,17)	NT	48.99***	89.94***	89.04***	123.13***	187.93***
Patients						
WS-GO	-0.26	-6.48	-7.58	-8.13	-10.31	-10.99
WS-STOP	-0.66	-5.00	-3.82	-2.73	-2.53	-2.89
F(1,17)	NT	1.75	7.35*	11.72**	27.08***	22.80***
<u>Pz Electrode</u>						
Controls						
WS-GO	2.79	-0.28	-3.36	-6.81	-9.10	-10.45
WS-STOP	2.49	2.52	1.01	-0.24	-1.37	-1.99
F(1,17)	NT	14.86**	35.09***	72.53***	99.98***	140.08***
Patients						
WS-GO	1.65	-0.53	-1.94	-4.24	-6.35	-7.32
WS-STOP	1.00	-0.29	-0.18	-1.05	-1.36	-1.83
F(1,17)	NT	0.09	4.28	14.60**	31.45***	34.16***

NT Not Tested

* $p < .05$

** $p < .01$

*** $p < .001$

Table 4-6

Results of Comparisons of Patient vs Control CNVs
for Each CNV Epoch in 2-Stimulus Condition¹

	Epoch					
	1	2	3	4	5	6
<u>Fz Electrode</u>						
Controls	-3.12	-5.77	-4.26	-5.88	-7.32	-9.70
Patients	-3.28	-8.22	-7.93	-7.49	-7.79	-8.37
F(1,34)	NT	3.62	10.66*	2.04	.13	.87
<u>Cz Electrode</u>						
Controls	-1.80	-5.72	-6.01	-8.25	-10.77	-14.11
Patients	-1.70	-6.57	-7.16	-7.92	-8.70	-9.65
F(1,34)	NT	NT	1.16	NT	2.51	8.97*
<u>Pz Electrode</u>						
Controls	2.23	-1.18	-1.81	-3.82	-5.57	-7.49
Patients	0.53	-2.32	-2.48	-3.95	-5.19	-5.98
F(1,34)	3.33	1.92	NT	NT	NT	3.25

1. Collapsed across IS and replication.

NT Not Tested

* $p < .01$

Table 4-7

Patients' Results for CNV, Reaction Time,
Somatosensory Evoked Potential, and CT scan

Pt.	Cortical Components					CT scan evidence	
	OVER	RT	of Median n. SEP			of localized lesions	
	UNDER		N20	P22	N30 P40	Hematomas	Contusions
PC			L			L insula	
BL			L			R frontal	
GW		+	B			R ventricle	
JB	+				L	cerebellum	
JM	+	+		B	B	B subdural	L diffuse
GM	+	+	L				B diffuse
GP	+	+				R fronto-temporal	R fronto-temporal
LS	+	+	B				R diffuse
BB	+	+					B frontal, L post temp
PD	+	+				B temporo-parietal	
KD	+	+				R temporal	
LD	+	+					
OE	+	+	L	B	B		
BG	+	+	L				
JH	+	+				R frontal	B diffuse
RL	+	+				B orbital	B parietal
SM	+	+	L		B	R frontal	
HM	+	+					

Note. OVER = Overprocessing; aberrantly large frontal CNV O-wave.
 UNDER = Underprocessing; aberrantly small central CNV E-wave.
 RT = One or more RT measures > 2 SD slower than control norms.
 + = Evidence of Underprocessing, Overprocessing, or slow RT.
 R = Aberrant finding for Right cerebral hemisphere.
 L = Aberrant finding for Left cerebral hemisphere.
 B = Bilaterally aberrant finding.

Conclusions

This study has brought new light to bear on the issue of the information processing deficits after severe closed head injury. Importantly, the demographic data presented in Chapter 2 indicates that the obtained results can be generalized to the population of survivors of severe CHI who go on to make satisfactory recoveries.

Neurosensory examination of 22 patients indicated that brainstem lesions are not a frequent consequence of severe closed head injury. However, there were several cases of damage to peripheral sensory systems, particularly the auditory system. Thus, similar reports which do not test the integrity of the peripheral sensory system should be interpreted with caution.

On the other hand, most patients showed signs of primary cortical dysfunction on somatosensory evoked potential testing. Taken together, results of cortical dysfunction without apparent involvement of lower centers lend credence to the concepts of Adams and colleagues (Adams et al., 1977, 1980, 1982) and Gennarelli and coworkers (Gennarelli, 1982; Gennarelli et al., 1978, 1982). These investigators have suggested that the functional and anatomical effects of acceleration/deceleration injury occur primarily at the cortical level, with brainstem structures injured last and least. It is also possible, though, that results obtained in the present study are due to the restricted sample of patients; recall that only patients who had made satisfactory recoveries were tested. Less satisfactory recoveries may indicate involvement of the brainstem, as in patient GK. The use of this sample was mandated, however, by the

requirement that patients be able to understand and adequately perform a rather complex reaction time task.

Results from the RT task replicated a number of other studies, by indicating significantly slow RT among the head injured. It is believed that the results of the CNV largely account for the slowing of RT. Only 1 patient who did not have slow RTs did not also have aberrant CNVs, and only 1 patient who had abnormal CNVs had slow RTs. Perhaps most importantly, 2 types of aberrant CNVs were found. Some patients exhibited an abnormally large and persistent frontal O-wave following a warning stimulus which indicated that a second stimulus could be ignored. This result was interpreted as a sign of overprocessing. That is, it is believed these patients devoted an inappropriate amount of time and energy to the processing of redundant and task-irrelevant information. Although no behavioral measures were obtained in trials in which overprocessing occurred, it is thought that the slow reaction times obtained from these patients result from the fatigue produced by their overvigilance.

Other patients generated an unusually small centro-parietal E-wave when a warning stimulus indicated that preparation for an upcoming behavioral response was necessary. This attenuation of the CNV was taken as evidence that these patients were not adequately preparing to respond; they underprocessed the information in the stimuli.

The concepts of under- and overprocessing may account for the contradictory findings of previous investigators. McCallum and Cummins (1973) and Rizzo et al. (1978) reported attenuated CNVs after head injury, while Curry (1980) reported supranormal CNVs after head

injury. It is possible that these investigators sampled only under- and overprocessors, respectively, perhaps through sampling error. Results from the current study do indicate that underprocessors outnumber overprocessors by about 2:1.

Importantly, the CNV changes reported here were not related to patients' demographic data, including severity of injury, age at injury, time since injury, or outcome. This finding suggests that signs of under- and overprocessing are likely, but unpredictable, outcomes of severe CHI. One variable that may be related to the two types of processing deficit is the location of prefrontal lesions. Clinical data suggests that underprocessing may be associated with dorsolateral prefrontal lesions, and a behavioral picture of hypoarousal, lethargy, and an air of indifference. Overprocessing may be a consequence of orbitofrontal lesions, and associated with disinhibited, aggressive, impulsive behaviors.

These findings may have particular relevance for the rehabilitation of the head injured, as the over- and underprocessing hypotheses suggest different, perhaps mutually exclusive rehabilitation strategies. The patient tending to overprocess information might benefit from a rehabilitation program similar to that used with children with attention deficit disorders. Such a regimen might use low-distraction environments, behavioral reinforcement for time-on-task, and perhaps low-dose methylphenidate drug therapy (M. L. Albert in Stern, 1978).

The patient who shows evidence of underprocessing information might also benefit from amphetamine-like medications (Stern, 1978). However, the behavioral approach for this patient would be very

different, with the emphasis on a more lively, active environment,
with rewards for speeded performance.

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HÔPITAL SAINT-VINCENT HOSPITAL
OTTAWA, ONTARIO.

REQUEST TO DO A RESEARCH PROJECT

ACCESS TO MEDICAL INFORMATION

I, J. Braxton Suffield, Carleton
(name) Ph.D. candidate, University
(credentials).

would like to do a research project at Saint Vincent Hospital in Ottawa.

The purpose of the research is for studying the long-term recovery of survivors
of severe closed head injury.

and the information I would require is medical records, to determine the initial
severity of injury (depth and duration of coma, results of EEG and brain scans).

I will not use the name of any patient nor will I release any information that
would violate the confidentiality of the information which I have received.

I will ~~will not~~ use the name of Saint Vincent Hospital in my report.

A copy of the final report will be sent to the Medical Record Department of
Saint Vincent Hospital.

Date: 27-MAR-85

Signature: J. Braxton Suffield

Witness: _____

I authorize J. Braxton Suffield to receive the information
requested in order to complete the project mentioned and this under the above
outlined conditions.

Date: March 27, 1985

Signature: [Signature]

Medical Director

HÔPITAL SAINT-VINCENT HOSPITAL

November 2, 1984

To Whom It May Concern:

On February 13, 1984 the Medical Advisory Committee of St. Vincent Hospital met and decided the following:

«Research Project-Revocery Process in Head Injury

The M.A.C., having examined the application for a grant to support the above-named project, considered the experimental procedure, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects».

Sincerely yours,

Michèle Scott
Administrative Secretary
Physical Medicine and Rehabilitation

/MS

GLASGOW OUTCOME SCALE.

NAME _____ CHART # _____ DOB (D-M-Y) _____
SEX _____ AGE _____ DATE OF HEAD INJURY _____ TODAY'S DATE _____

CIRCLE ONE OUTCOME CATEGORY:

(Dependent)	(Independent)
PERSISTENT VEGETATIVE STATE	MODERATE DISABILITY
SEVERE DISABILITY	GOOD RECOVERY

DEFINITIONS:

PERSISTENT VEGETATIVE STATE

No awareness or speech
No response to external stimuli
Cycles of sleep and wakefulness present

SEVERE DISABILITY

Severe FUNCTIONAL disability
Conscious but dependent
Significant cognitive or physical handicaps or both.
Dependent in one or more activities
(ambulation, transfers, transportation, etc.)
Patient may not be left overnight
(inability to cope with callers, crises, meals, etc.)
May or may not be institutionalized
Some communication present
Some ambulation possible
Some self-care possible

MODERATE DISABILITY

Independent but disabled
Independent in extended daily tasks
(self-care, cooking, public transportation, shopping, etc.)
Moderately severe residual deficits
(aphasia, hemiparesis, ataxia, memory, personality, IQ, etc.)
Could work in sheltered environment, but may not

GOOD RECOVERY

Patient may not have resumed normal life, but the capacity is there.
Could work in competitive occupation, but may not
Mild - Moderate neurological, psychological deficits may persist.
May pursue leisure activities
May pursue occupational activities

DISABILITY RATING SCALE

Appendix D

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NAME _____ CHART # _____ DOB (D-M-Y) _____
 SEX _____ AGE _____ DATE OF HEAD INJURY _____ TODAY'S DATE _____

CATEGORY	ITEM	CRITERION	SCORE (one per group)
Arousalability, Awareness and Responsivity (Glasgow Coma Scale)	Eye Opening	spontaneous	0
		to speech	1
		to pain	2
		none	3
	Verbalization	oriented	0
		confused	1
		inappropriate	2
		incomprehensive	3
		none	4
	Motor Response	obeying	0
		localizing	1
		withdrawing	2
		flexing	3
		extending	4
		none	5
Cognitive Ability for Self Care; Does Patient Know How and When? Ignore Motor Disability	Feeding	Complete	0
		Partial	1
		Minimal	2
		None	3
	Toileting	Complete	0
		Partial	1
		Minimal	2
		None	3
	Grooming	Complete	0
		Partial	1
		Minimal	2
		None	3
Dependence on Others	Completely independent		0
	Independent in special environment		1
	Mildly dependent; needs limited assistance (non-resident helper)		2
	Moderately dependent; needs helper in home		3
	Markedly dependent; needs help with all major activities at all times		4
	Totally dependent; needs 24hr nursing care		5
Psychosocial Adaptability and Employability	Not restricted		0
	Selected jobs, competitive		1
	Sheltered workshop, non-competitive		2
	Not employable		3

Score	Disability	Score	Disability	Score	Disability	Total Score
0	none	7-11	mod. severe	25-29	ext. veg. state	_____
1	mild	12-16	severe	30	death	
2-3	partial	17-21	extr. severe			
4-6	moderate	22-24	veg. state

HÔPITAL SAINT-VINCENT HOSPITAL

INFORMATION FOR VOLUNTEERS

The study you are about to participate in involves the recording of your electroencephalogram (EEG) while you listen to clicks, watch checks on a television, and feel a mild stimulation near your wrist. The purpose of the study is to investigate differences in the averaged EEG between people who have or have not had head injuries. There are no risks or pain involved in the tests. However, some people find the mild stimulation on the arm uncomfortable. In addition, you may have a small amount of glue or paste in your hair at the end of the test, from the way we keep electrodes on your head. Should you wish, you may withdraw from the study at any time.

CONSENT:

I have read the above «Information for Volunteers», and understand the nature and purpose of this study, which is being carried out by Dr. R. El-Sawy, Braxton Suffield, and Dr. Kenneth Campbell. I give my informed, voluntary consent to participate.

Name (Print Please)

Signature

Date

INFORMATION FOR SUBJECTS

The study you have been asked to participate in involves the recording of your electroencephalogram (EEG) while you listen to tones through headphones. You will be asked to press a button when you hear certain tones.

You may also be asked to watch colored lights on a panel, and to press a button when you see certain colors.

The purpose of the study is to investigate differences in the averaged EEG between people who have or have not had head injuries. There is no pain or risk involved in the tests. However, you may have a small amount of glue or paste in your hair at the end of the test, left over from the way we keep electrodes on your head. We will do our best to remove this before you go home. Should you wish, you may withdraw from the study at any time.

CONSENT

I have read the above "Information for Subjects," and understand the nature and purpose of the study, which is being carried out by Dr. Kenneth Campbell, Dr. R. El-Sawy, and Braxton Suffield. I give my informed, voluntary consent to participate.

Name (please print)

Signature

Date

END

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