(v) Neuropsychological Deficits Following Head Injury in Children

(a) Intellectual Impairment

A considerable number of investigators have examined intellectual functioning in head-injured children. Almost invariably, the dependent measures in these studies have been one or more intelligence quotients (IQs) derived from the most popular intelligence tests, particularly the Wechsler scales. A smaller number of studies have also reported quantitative measures of motor functioning and sensory/perceptual functioning after head injury. These are reviewed below.

The earliest commonly-cited quantitative assessment of IQ in head-injured children were reported by Richardson in 1963. Richardson found losses of 10-30 IQ points among 10 children who had suffered severe concussions at least two years prior to assessment. He also reported a greater than normal range of variation in the individual child's intellectual abilities. While this early study did suggest that children's intellectual abilities are not spared following trauma, the data are questionable for several reasons. First, the reported decrements in IQ were based on estimates of pre-injury IQ derived from sources including school records and parental observations. While Richardson (1963) claims that these estimates are accurate to within 10-20 IQ points, this is likely not verifiable. Second, the finding of abnormal variability appears to be based upon clinical impressions as no normative

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Services des thèses canadiennes

Ottawa, Canada
K1A 0N4

CANADIAN THESES

THÈSES CANADIENNES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

**THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED**

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30.

**LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE**

Reaction Times and Speed-Accuracy Tradeoff
Strategies in Head-Injured and Normal Children

H.W. Winogron

Thesis presented to the Faculty of Graduate Studies
in partial fulfillment of the requirements for the

degree of

Doctor of Philosophy

Department of Psychology

Carleton University

© March 1986

Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

L'autorisation a été accordée à la Bibliothèque nationale du Canada de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur (titulaire du droit d'auteur) se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation écrite.

ISBN 0-310-29860-X

The undersigned hereby recommend to the Faculty of
Graduate Studies and Research acceptance of the thesis,

submitted by

H.W. Winogron

in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

.....
Chairman, Department of Psychology

Robert M. Knights
.....
Thesis Supervisor

W. H. Marshall
.....
External Examiner

Carleton University

April, 1986

ABSTRACT

Three separate experiments investigated speed of responding and speed-accuracy tradeoffs in severely head-injured, mildly head-injured, and normal control children. All groups were matched for age and sex, and the head-injured groups were matched for injury-test interval, which was about two years. Experiment I employed a simple visual reaction time (RT) task with variable foreperiods (FPs) of 1-5 sec. RT was a declining function of FP to 4 sec and levelled off at 5 sec. Severely-injured Ss were significantly slower overall, but the interaction between group and FP was not significant, indicating that head-injured and control children processed probabilistic information about the temporal distribution of FPs in much the same way. Intra-subject variability decreased for all groups as FP increased. While the severe group showed the greatest variability, the relation between FP and variability was constant across groups. Skewedness of RT distributions did not differ across groups. The relations of IQ and motor measures with RT were also discussed.

Experiment II used a line-length comparison, in which both the child's accuracy and speed of responding could vary. While accuracy did not vary significantly between groups, the severely-injured group made correct responses more slowly than either the mildly-injured or control groups.

Experiment III used the same task as Experiment II, modified to include three criterion times (CTs; 2000, 1500, 1000 msec) and instant visual feedback concerning response speed and

Experiment III used the same task as Experiment II, modified to include three criterion times (CTs; 2000, 1500, 1000 msec). and instant visual feedback concerning response speed and accuracy. Significant effects for CT indicated that even the severely-injured could hasten their responses with only a minimal sacrifice of accuracy. Speed-accuracy tradeoffs were similar across groups suggesting that information processing is the same for all three groups. The implications of these findings, and suggestions for future research were discussed.

DEDICATION

I dedicate this dissertation to my mother and to the memory of my father. They have filled their sons with self-confidence and the desire to succeed in all their undertakings.

ACKNOWLEDGEMENTS

I thank Dr. Robert Knights for his supervision over the last several years. He has raised me from my academic youth, and taught me, among other things, not to fret about life. Sincere thanks also to Dr. Bill Jones who co-supervised this dissertation, and similarly instilled in me a clearer view of the 'big picture'. The help of both my advisors has been invaluable. I thank Dr. L.P. Ivan, Chief of the Division of Neurosurgery at C.H.E.O., for allowing me to test his patients, and Dr. J. Goodman, Director of Psychology at C.H.E.O. for giving me access to hospital facilities. Thanks also to Kathy Malizia for her patience and encouragement and statistical help. Thanks to Mr. Fitchet and his staff at Hopewell School, and to Doug Yuill for making my testing easier. I am indebted to the parents of the participating children, and to the children themselves for their cooperation. I greatly appreciate the encouragement offered by my friends, especially Jim Irving, Paul Durber, and Johnny Moisey. Finally, I thank my brothers for going to the movies with me so often, and helping me to be cheerful about it all.

TABLE OF CONTENTS

Dedication
Abstract
Acknowledgements

INTRODUCTION	1
(I) The Head Injury Syndrome	1
(i) Epidemiology	1
(ii) Mortality	1
(iii) Causes	2
(iv) Neuropathology	3
(v) Neuropsychological Deficits	11
(a) Intellectual deficits	11
(b) Relation of IQ to injury severity	14
(c) Other neuropsychological deficits	20
(II) Reaction Time Following Head Injury	25
(i) Definition and Introduction	25
(ii) Review of the Literature	28
(iii) Reaction Time in Pediatric Samples	34
(iv) Summary and Evaluations and Goals of Current Research	35
(III) Statement of Hypotheses	42
(IV) General Description of Experiments	45
Subjects	45
Apparatus	54
(V) EXPERIMENT ONE	55
Procedure	55
Results	58
Discussion	70
(VI) EXPERIMENT TWO	82
Procedure	84
Results	85
Discussion	94
(VII) EXPERIMENT THREE	103
Procedure	103
Results	105
Discussion	110
(VIII) GENERAL DISCUSSION	115
REFERENCES	126
APPENDICES	140

INTRODUCTION

(I) The Head Injury Syndrome

(i) Epidemiology of Closed Head Injury in Children

In a recent book on the topic of head injury, Levin, Benton and Grossman (1982) state that "accurate incidence and prevalence statistics for closed head injury in children are unavailable because of the lack of a centralized system for case ascertainment" (p. 192). Studies conducted in Britain in recent years do, however, give an indication of the magnitude of the problem: Of all children under age 15 years admitted to hospital, 16 per cent have been involved in accidents, with more than one-third of all accident victims receiving head injuries. It was further found that 41 per cent of deaths in children involved head injury (Craft, 1972; Field, 1976; Jamieson & Kaye, 1974).

(ii) Mortality

Mortality rates following closed head injury are reportedly lower for children than adults (Bruce, Schut, Bruno, Wood, & Sutton, 1978; Craft, 1972; Hendrick, Harwood-Hash, & Hudson, 1984). This is best demonstrated by comparisons of mortality for adults and children who have been matched for severity of injury: Mortality rates of 30-50 per cent have been reported for adults admitted to hospital with scores of seven or less (of a possible 14, which indicates normal consciousness) on the Glasgow Coma Scale (GCS), a measure of coma severity (Becker, Miller, Ward, Greenberg, Young, & Sakalas, 1977; Jennett,

Teesdale, Galbraith, Pickard, Grant, Braakman, Avexaat, Maas, Minderhoud, Vecht, Heiden, Small, Caton, & Kurze, 1977). A mortality rate of nine per cent has been reported for children admitted with GCS scores of less than eight (Bruce, Schut, Bruno, Wood, & Sutton, 1978). Hendrick, Harwood-Hash and Hudson (1964) have reported comparable rates for children with GCS scores below eight.

The possibility that coma may be more readily induced in children (precipitated by less injury to the brain than in adults) may account for the differences in prognosis. This issue has not been investigated.

(iii) Factors Associated with Head Injury (Including Cause of Injury)

The most frequent cause of head injury in the pediatric population, accounting for about one-half of cases, is falls (from bicycles; down stairs, etc.), and the next most common cause is road traffic accidents, accounting for about one-third of reported cases (Levin et al., 1982). These accidents most often involve pedestrian-car collisions, and in late adolescence, victims are more frequently passengers in cars when they are injured.

The ratio of males to females among head-injured populations (closed head injuries) ranges from 2:1 to 3:1 (Craft, 1972; Field, 1976; Hendrick et al., 1964) with the 2:1 ratio seemingly accepted by practitioners in the area. This male predominance among children injured before age five years is less marked.

A study which examined the incidence of children's head

injuries as a function of age (Annegers, Grabow, Kurland, & Lews, 1980) reported, at least for one county in Minnesota, a dramatic increase in incidence for "children" aged 15-24 years.

A British survey (Field, 1976) has found, perhaps not surprisingly, that head injuries occur most frequently in the time period between dismissal from school and early evening. Head injuries are also more common among children from families of lower socio-economic status (SES) according to a Canadian study (Klonoff, 1971).

(iv) Neuropathology of Head Injury

The two principal subcategories of head injury are missile or "penetrating" injuries and non-missile injuries known as "blunt" or "closed" head injuries.

Missile head injuries result when objects moving through space collide with the head. The size and severity of resultant wounds is dependent upon the fixedness of the head (i.e., its freedom to move through space) as well as the nature of the projectile (size, weight, shape), its speed of travel, and the angle or direction of the impact.

Non-missile or "blunt" or "closed" head injuries occur when the head's movement is rapidly decelerated through contact with an object, or when a moving object strikes a stationary or slower-moving head (Gurdjian, 1971). These injuries involve a different pathogenesis than do missile injuries. Generally, the damage in closed head injury can be divided into that which is directly attributable to impact (primary), and that which is not

(Adams, 1975; Adams & Graham, 1972). In the former category, damage is caused by the force brought about at the time of impact, and although the damage often occurs immediately, it may also be delayed. Immediate damage may consist of relatively focal macroscopic lesions including coup and contrecoup contusions (bruises at the site, and opposite to the site of impact), brain laceration, and damage to nerve fibers and blood vessels, or it may consist of diffuse microscopic lesions resulting from the widespread stretching of nerve fibers (Adams, Mitchell, Graham, & Doyle, 1977; Strich, 1956). Damage directly attributable to impact forces can also be delayed, i.e., occurring following some interval, but nevertheless attributable to a process which began at the time of impact. The most common types of this delayed impact damage are intracranial hemorrhage and brain swelling.

The severity of immediate and delayed impact damage varies from trivial to fatal, with death resulting from a combination of focal and diffuse injuries (usually when survival after injury is brief) or from severe diffuse damage (usually when survival is more prolonged) (Adams, 1975).

Secondary brain injury results from processes which are not directly attributable to impact. The mechanisms of such damage may include expanding intracranial lesions, cerebral infections, and systemic circulatory disturbances affecting cerebral blood supply (Adams & Graham, 1972; Adams, 1975).

The principal types of brain damage resulting from closed head injury are now briefly summarized.

a) Damage directly attributable to impact: immediate type

Contusions are the characteristic focal brain lesion associated with non-penetrating head injuries (Adams, 1975). It is worth noting, however, that focal mass lesions in closed head injury do not appear to have the same neuropsychological repercussions as do such lesions in penetrating head injuries (e.g., Newcombe, 1969). Distortion of the skull, principally a bending-inwards, is the main cause of coup contusion (Ommaya, Grubb, & Naumann, 1971). It is important to note that while a discrete localized area of impact will likely result in a subjacent coup surface contusion, collision with a flat surface does not usually cause coup contusions (Gurdjian & Gurdjian, 1976). Contrecoup or intermediate coup contusions are those which occur at points distant from the site of impact. These lesions most frequently result when the brain moves within the skull and collides with, or is compressed by, parts of the skull (Courville, 1945). Deeper contusions occurring within the brain substance at some distance from the impact site are the result of stresses from the relative movements of the brain or "inertial stress propagation" (Gurdjian & Gurdjian, 1976, p. 35). Contrecoup lesions occur most frequently in the fronto-temporal regions of the brain, irrespective of the site of impact, because of the relatively great restraint of these areas by the sphenoid ridges and other irregularities in the base of the skull (Ommaya et al., 1971).

Degeneration of neural fibers can occur following blunt head injury. While still controversial, the cause of this

degeneration is thought to be direct tearing of nerve fibers resulting from the mechanical shear-strain occurring at the time of impact (Strich, 1956; 1961; 1969; 1970). Holbourn (1943) hypothesized that rotational acceleration of the cranium would cause a pulling apart, or discontinuity, of axons as well as the damage of cell bodies (a "shear strain"). Using models of the skull and brain he demonstrated that such shear strain does exist when the head is free to move (i.e., not held in a fixed position) and is maximal in the anterior portion of the temporal lobe. Studies employing rhesus monkeys whose calvaria had been replaced by transparent covers have confirmed that the brain swirls relative to its encasement following impact (Prudenz & Sheldon, 1946), even when the impact does not cause concussion.

Holbourn's (1943) finding that shear-strains are not equal in all parts of the brain was supported in experimental work by Ommaya and Gennarelli (1974). These authors demonstrated that the diffuse injury associated with shear strain is greatest in areas where the shape of the skull is irregular (i.e., temporal lobe or frontal pole) and least where there was less roughness, or fewer protuberances (occipital lobe).

On the basis of Holbourn's (1943) brain model studies and mathematical models of brain translation and rotation (Advani, Owings, & Schurck, 1972), as well as their own study of experimental head injury in monkeys, Ommaya and Gennarelli (1974) hypothesized that "rotational components of accelerative trauma to the head produce a graded centripetal progression of diffuse cortical-subcortical disconnection phenomena which is always

maximal at the periphery..." (p. 652). According to this hypothesis, the surface of the brain is first affected, and the damage extends "inward" or subcortically in the case of severe head injury.

The Ommaya and Gennarelli hypothesis predicts that, in cases where the head is accelerated or decelerated at impact, if an injury is sufficiently severe to cause unconsciousness, structural disruptions will be more severe in cortical and subcortical structures than in the rostral brain stem, which is implicated in the production of traumatic unconsciousness. The authors report that experimental and clinical findings regarding altered consciousness and the distribution of damage in the brain following head injury support this prediction (see Ommaya & Gennarelli, 1974).

b) Delayed impact injury

Edema, which is the build-up of excess water in brain tissue, is often seen in the white matter around hematomas and contusions (Adams, 1975). Traumatic edema is believed vasogenic (Klatzo, 1975), that is, the water leaks from damaged blood vessels and moves extracellularly to the adjacent white matter. It is unknown whether edema actually directly damages brain tissue, but it can contribute to the effect of an expanding mass lesion (Levin, Benton, & Grossman, 1982).

Diffuse swelling of both cerebral hemispheres is frequently seen in children within 24 hours of severe head injury and may occur as soon as 20 minutes post-injury (Kobrine, Timmins,

Rajjoub, Rizzoli, & Davis, 1977). Causes for the swelling are likely transitory hyperemia, or excess cerebral blood flow possibly caused by arterial dilation resulting from vasomotor paralysis (Langfitt, Tannenbaum, & Kassel, 1966), or "increased vascular permeability" (Adams, 1975, p. 52) resulting from the shear strain on blood vessels.

Intracerebral hematomas are localized collections of blood, usually clotted, which have been discharged from vessels into the brain. These space-occupying lesions are typically related to contusions and therefore have a similar anatomic distribution (Adams, 1975). They occur in 30 to 40 per cent of severe head injury patients admitted to university hospitals (see Miller, Butterworth, Gudeman, Faulker, Choi, Selhorst, Harbison, Lutz, Young, & Becker, 1981). Microscopic hemorrhages frequently occur deep within the cerebral hemispheres (particularly in the subcortical white matter and corpus callosum), presumably because of tears in blood vessels caused by shearing strain (Strich, 1970).

Lindenberg (1971) report that epidural hematomas occur in only about two per cent of all types of head injury. These lesions occur between the dura and skull due to hemorrhage of the meningeal vessels, and they indent the subjacent brain. Skull fracture is present in the majority of cases (Janiéson & Yelland, 1968). These hematomas are most common in the temporal region because of tearing of the middle meningeal artery.

Subdural hematomas are collections of blood in the subdural space resulting from rupture of the small vessels which bridge

this space (Adams, 1975), or from tears in the cerebral arteries or damages to sinuses on the brain surface (Levin et al., 1982). When large, these hematomas are often associated with adjacent contusions. Subdural hematomas may be acute, subacute, or chronic, and can follow seemingly mild head injuries with few signs of primary impact damage (Maloney & Whatmore, 1969). The incidence of subdural hematomas is difficult to ascertain, with reports of acute subdural hematomas occurring in 26 per cent (Maloney & Whatmore, 1969), 45 per cent (Adams, 1975) and 63 per cent (Freytag, 1963) of patients with non-missile head injuries.

c) Damage not attributable directly to impact

Extradural or subdural hematomas or diffuse cerebral edema may be extremely important, sometimes fatally important, factors in head injury. While these factors are discussed individually above, it is important to note that any expanding lesion within the cranium can cause increases in intracranial pressure which can distort and herniate the brain (Adams, 1975). In fact, the effects of increased intracranial pressure can at times be the only recognizable brain abnormalities in cases with mild impact injuries. Thus, aside from the specific effects of these lesions, secondary effects, or those effects not caused directly by impact must also be considered.

Ischemia is probably the result of inadequate systemic blood circulation and/or compression of cerebral arteries resulting from increased intracranial pressure (Jellinger & Seitelberger,

1970; Lindenberg, 1971)). It is an important factor contributing to mortality in non-survivors, and to disability in survivors.

Summary and Comment Concerning Neuropathology

As stated above, brain damage in cases of closed head injury is caused by different processes, and may have different repercussions, than brain damage in open or penetrating head injuries. Rotational acceleration or deceleration of the brain may cause stretching of nerve fibers and the occurrence of widespread microscopic lesions. Also, brain swelling and focal pathologic processes result in a generalized increase in intracranial pressure, believed to be an important determinant of secondary brain damage. Overall, the picture which emerges is one of mild-to-moderate, diffuse, widespread damage to subcortical and particularly cortical structures. Not surprisingly, therefore, the bulk of research into the psychological effects of closed head injury has not focused on anatomical-psychological relationships (i.e., the effects of focal brain damage) but rather has emphasized the relation of psychological deficits to global indices of injury severity such as coma duration and post-traumatic amnesia.

(v) Neuropsychological Deficits Following Head Injury in Children

(a) Intellectual Impairment

A considerable number of investigators have examined intellectual functioning in head-injured children. Almost invariably, the dependent measures in these studies have been one or more intelligence quotients (IQs) derived from the most popular intelligence tests, particularly the Wechsler scales. A smaller number of studies have also reported quantitative measures of motor functioning and sensory/perceptual functioning after head injury. These are reviewed below.

The earliest commonly-cited quantitative assessment of IQ in head-injured children were reported by Richardson in 1963. Richardson found losses of 10-30 IQ points among 10 children who had suffered severe concussions at least two years prior to assessment. He also reported a greater than normal range of variation in the individual child's intellectual abilities. While this early study did suggest that children's intellectual abilities are not spared following trauma, the data are questionable for several reasons. First, the reported decrements in IQ were based on estimates of pre-injury IQ derived from sources including school records and parental observations. While Richardson (1963) claims that these estimates are accurate to within 10-20 IQ points, this is likely not verifiable. Second, the finding of abnormal variability appears to be based upon clinical impressions as no normative

data were reported. Also, the use of a small and heterogeneous sample selected on the basis of prolonged coma (coma was undefined) or post-traumatic amnesia (PTA), without any attempt to relate the nature or severity of injury to outcome, reduces the utility of these results.

A more methodologically sound study by Klonoff, Robinson and Thompson (1969), compared IQ scores (collected as part of a full neuropsychological assessment) of a group of 74 head-injured children and a group of chronically brain-damaged children (e.g., meningitis, encephalitis) to scores for groups of matched normal controls. The Stanford-Binet intelligence test was used with children under five years of age and the Wechsler Intelligence Test for Children (WISC) was used for older children. The results showed that both patient groups fared significantly worse than their respective controls. IQs for the head-injured children, the majority of whom sustained neurologically severe injuries, ranged from 46 to 135 with a mean of approximately 101, which was 12 points lower than the mean for controls. While this deficit is within the range of intellectual decline reported by Richardson (1963) in the aforementioned study, these patients were tested soon after injury (range 1-86 days, median 10.8 days) and would still be expected to show substantial recovery over time.

IQ decrements similar to those reported by Richardson (1963) were reported by Flach and Malmros (1972) in a long-term follow-up of severely head-injured children. Of the 125 patients tested by these authors, almost one-half showed "mental

disturbance", the most frequent disturbance being "mental deterioration" i.e., reduced Performance IQ and a wide dispersion of subtest scores. These authors unfortunately did not report the extent of IQ reduction and, as was also true of Richardson's (1963) report, they did not state whether the subtest dispersion was abnormal with respect to a comparable (i.e., same IQ) normative group. Nevertheless, the pattern suggests a trend.

The change in IQ scores over time was nicely examined by Klonoff and his associates in a subsequent longitudinal study of head-injured children (Klonoff, Low, & Clark, 1977). In this study, IQs for head-injured children measured at the time of hospitalization and again five years later, were compared to those of normal controls. The head-injured patients were divided into two groups, one having residual neuropsychological deficits, the other not. It was found that all three groups differed significantly at the initial testing with IQs of approximately 115 for normals, 106 for head-injured patients without residual deficits, and 92 for head-injured children with residual deficits. The group without residual deficits improved substantially over the five years and their scores at this time did not differ from those of controls. The group with residual deficits, although they had a mean IQ of about 99 after five years, were significantly below controls (mean of 120). A problem with the Klonoff et al. (1977) study is the poor description of the neurologic severity of the injuries sustained by the sample.

A group of researchers from California (Brink, Garrett, Hale, Woo-Sam, & Nickel, 1970; Woo-Sam, Zimmerman, Brink, Ueyhara, & Miller, 1970) reported on the relationship between age and post-traumatic intelligence. They found that among 46 severely head-injured children experiencing coma longer than one week, about two-thirds showed lower than normal IQs, and that younger children (ages 2-8) showed poorer recovery than did older children (ages 10-18).

Because the younger and older groups were not equated for severity of injury, this result must be interpreted cautiously. However, comparison of coma durations for the two groups indicates that the younger children (despite their poorer recoveries) had shorter comas, implying milder injuries.

To summarize the findings to this point, children's IQ scores tend to be reduced after head injury by perhaps 10-30 points. Although improvements in these scores over time are typical, deficits (relative to neurologically intact controls) tend to persist, particularly in younger children and children with residual neuropsychological deficits.

(b) Relationship of Injury Severity to Post-Traumatic Intellectual Functioning

While the above-described research findings have linked the occurrence of head injury to the existence of intellectual deficits, their utility is limited, particularly with respect to prediction of expected outcome for individual patients. The findings reviewed below concern the relationship between the

severity of injury and intellectual deficits.

A number of studies have reported an inverse relationship between duration of coma after head injury and post-traumatic IQ (Brink et al., 1970; Johnston & Mellita, 1980; Levin & Eisenberg, 1979a, b; Woo-Sam et al., 1970). Brink et al. (1970) reported that coma duration was inversely related to IQ measured at least one year post-trauma, and that patients with IQs in the normal, borderline, mildly retarded, and severely retarded ranges had average comas of 1.7, 3, 8, and 11 weeks respectively. It was later reported (Woo-Sam et al., 1970) that, in this sample, the relationship between coma and outcome was independent of the age and socio-economic status of the patients. However, these authors did not define their criteria for coma, did not consider patients with coma shorter than one week, and did not report how much time had passed between injury and IQ testing for individual patients or for the group as a whole.

Levin and Eisenberg (1979b) compared IQs for patients with brief or no loss of consciousness after injury with those in coma less than one day, and those in coma longer than one day. These authors assessed IQ between approximately one-half and three years post-trauma, and the average follow-up interval was one and one-half years. They found that Verbal IQ was significantly lower for patients with coma longer than one day than for those with coma less than one day. Unequivocal impairment of intellect, defined as IQ below 70, was found only in four patients, all of whom were in coma longer than one day.

Johnston and Mellits (1980) considered only patients who were in coma more than one day and were subsequently admitted to a rehabilitation clinic. By not considering patients with comas lasting less than 24 hours, or patients not requiring placement in a rehabilitation setting, these authors eliminated all but severely-injured children. Results showed that, an average of 10 months post-trauma, coma duration was significantly inversely related to IQ or DQ (an estimated developmental quotient).

It appears that although different definitions of coma, different injury-test intervals, and somewhat different measures of outcome were employed in the above studies, there is a tendency for children with longer comas to suffer greater intellectual disturbances after head injury. Methodological differences across studies preclude the definition of a threshold, above which intellectual deficit necessarily occurs.

As discussed above, Klonoff et al. (1977) compared IQs for children with residual neuropsychological deficits with those of patients without residual deficits and with those of normal controls. It is noteworthy that this grouping is based upon psychological, rather than neurological indices of severity of head injury. Results indicated that IQs were significantly lower among patients with residual neuropsychological deficits, both at the time of injury and five years later. IQs for the group without residuals did not differ at five year follow-up from those of normal controls. Another interesting finding was that in a multiple regression analysis, Full Scale IQ, taken close to the time of hospital admission, was the best predictor

of residual neurological sequelae.

The use of a post-traumatic psychological score to predict severity of neurologic deficit is opposite, conceptually, to the approaches taken above. Nevertheless, the finding demonstrates a significant relationship between psychological and neurological deficits after head injury in children.

Chadwick, Rutter, Brown, Shaffer and Traub (1981a) investigated the relationship between IQ and an alternate measure of injury severity, post-traumatic amnesia (PTA), which is a measure of the time during which a patient is incapable of storing new memories after an injury. They intellectually assessed severely-injured patients (PTA longer than 1 week), orthopedically-injured controls, and a group of mildly-injured patients (PTA longer than 1 hour, but less than 1 week). These assessments were conducted immediately post PTA, and then at 4, 12, and 30 months post-trauma. Their relevant findings were as follows: (1) a strong inverse relationship between duration of PTA and intellectual impairment was found only among the severely-injured patients, (2) the existence of intellectual impairment was related to the presence of abnormality on neurologic examination only among the severely-injured and, (3) patients with PTAs of three weeks or longer were "well below their matched controls on all aspects of intellectual functioning throughout the 2-3 years of follow-up" (p. 55), whereas those with PTAs of 2-3 weeks showed smaller and less persistent deficits, and those with PTAs of 1-2 weeks showed no significant deficits even at the first assessment.

Generally, it can be argued that PTA duration, like coma duration, appears related to post-traumatic intellectual function in children. PTA however, offers a more retrospective measure of injury severity than does coma duration and is therefore not as usefully applied to the early management of head injury patients as are coma measures (Stover & Zeriger, 1976). Carlsson, Von Essen and Lofgren (1968) have noted that PTA is dependent upon the pre-traumatic capacity of the brain and is influenced by the patient's age. Because of these limitations, and because of the availability of relatively objective measures of the depth and duration of coma (Teasdale & Jennett, 1974) in addition to measures of the duration of coma, coma appears to be the most promising neurologic tool for the study of neurologic/psychologic relations after head injury currently available.

Winogron, Knights, and Bawden (1984) examined the relationship between coma severity or "depth" of coma, and post-traumatic intellectual deficits. They reported significant correlations between scores on the Glasgow Coma Scale (GCS) (Teasdale & Jennett, 1974) and Verbal, Performance, and Full Scale IQs on the WISC-R. The GCS is a 14-point index of depth of coma; the scale has satisfactory reliability and validity. The Performance scores showed the strongest correlations to coma severity. In addition, the Performance and Full Scale scores were significantly inversely correlated (albeit to a lesser extent) with the duration of altered consciousness, defined as the time elapsed after injury before a full score was attained.

on the GCS. This definition was adapted by Winogron et al. (1984) in order to avoid the theoretical and practical problems (see Jennett, 1972) involved in defining the end of coma. When Verbal, Performance, and Full Scale IQs were compared across three groups defined on the basis of a composite rating of neurologic severity of injury (which considered the nature and severity of the insult), it was found that all three groups differed from each other on Performance IQ only, with the ordering of groups being mild, moderate, and severe from least impaired to most impaired.

Differential reduction on Verbal and Performance IQ scales have been reported by other authors. Wop-Sam et al. (1970) for example, reported that the mean Performance IQ was 12 points lower than Verbal IQ for a group of severely-injured children, but did not report statistical analyses. Flach and Malmros (1972) reported reduced Performance IQs and wide subtest scatter as the most frequent long term sequelae of severe head injury. They did not, however, report statistical analyses, and other methodological problems with their study have been described above. The most notable results have been reported by Chadwick and his co-workers. Chadwick, Rutter, Shaffer and Shrout (1981a) found that Performance IQ, but not Verbal IQ was significantly reduced in a group of severely head-injured children relative to a group of non-neurologically injured controls up to 2 1/4 years post-trauma. Also, differences in Verbal and Performance IQ scores were found to be significantly larger among severely head-injured children than among

midly-injured and non-neurologically-injured children, with Performance scores showing greater impairment than Verbal scores in the first year after injury (Chadwick et al., 1981a):

(c) Other Neuropsychological Deficits

Motor and sensory/perceptual abilities have been studied in head-injured populations although not nearly to the same extent as intellectual functioning. Attempts have also been made to investigate the relationships between such deficits and the neurological severity of injuries sustained. Studies considering these issues are reported here.

Brink et al. (1970), in addition to examining IQ scores in severely-injured children, also examined motoric function. Spasticity and ataxia were found to be the most frequent motor defects occurring in 93% and 70% of their sample, respectively. Average coma duration for this sample was seven weeks, and at least partial recovery of motor skills was observed in all patients who regained consciousness, even following prolonged coma. Other deficits mentioned by Brink et al. (1970) were sensory deficits, visual disturbances, and speech disabilities. However, these deficits were not described or evaluated in any systematic fashion, and no attempt was made to examine how these deficits (including motor problems) related to injury severity.

Klonoff and his associates (Klonoff, Low, & Clark, 1977) employed a comprehensive neuropsychological test battery in the longitudinal evaluation of head injury patients. Patients were tested at the time of hospital admission and then yearly for

five consecutive years. Results indicated that 29 of 32 comparisons of test scores between a younger patient group (<9 years) and matched non-neurologically injured controls, and 43 of 48 comparisons between a group of older patients (>9 years) and controls, revealed significant differences over all five years combined. Comparisons between head-injured children and controls at the time of initial hospitalization and at one year revealed deficits which included slowed finger and foot tapping, slowed visuo-motor performance on the trails making test, formboard assembly, and mazes tests.

Recovery on the neuropsychological battery was found to be slower than recovery on normal EEG but faster than neurological recovery (assessed clinically). While the majority of patients showed marked improvement over the course of the study, about one-quarter still showed neuropsychological deficits at final follow-up. Significant improvements continued over all five years of the study, but gains were maximal during the first year post-trauma. An earlier report by Klonoff, Robinson and Thompson (1969), while essentially presenting similar findings, also reported that the neuropsychological impairment index (a summary measure of neuropsychological deficit) was not found to be significantly related to neurologic and electroencephalographic indices of impairment.

Levin and Eisenberg (1979a, b) administered a large number of tests to head injured children soon after their injuries (median injury-test interval and range, 19 and 1-185 days) and compiled the results to derive composite measures of language,

visuospatial, memory, and somatosensory functions and motor speed. They found about half of the patients to have memory deficits on the selective reminding test (Buskirk & Fuld, 1974). This is not surprising in view of the fact that a short injury-test interval was used and a number of patients were still mildly confused at the time of testing. Serial examination of two head injured patients with this same test (Fuld & Fisher, 1977) has shown the recovery of long-term memory to be slower than recovery of motor function. Verbal memory deficits have been reported for nearly one-quarter of patients followed-up almost a decade after head injury with coma (Gaidolfi & Vignolo, 1980). Fewer patients have shown spatial memory problems.

Levin and Eisenberg found that about one-quarter to one-third of their patients were deficient in each of the remaining composite test areas. The proportion of patients showing memory and visuospatial deficits was significantly higher among more severely injured patients; those who were in coma (unresponsive to commands) less than 24 hours but showed signs of neurologic deficit, and those in coma longer than 24 hours showed more deficits than those who did not lose consciousness or did so only briefly and without signs of neurologic deficit.

GCS scores at the time of hospital admission were also related to outcome. Memory and visuospatial deficits were significantly more common in patients with low scores on the verbal responsiveness scale, also, a trend for more frequent memory and visuospatial problems to be associated with poor

motoric responsiveness occurred. GCS scores were not related to the composite functions of language, somatosensory ability, and motor speed. However, it should be remembered that the motor and verbal responsiveness scales of the GCS were considered separately by Levin and Eisenberg, and the eye-opening scale was not used. No attempt to relate neuropsychological functioning to the composite GCS scores was reported even though available reliability and validity data for the GCS pertain largely to the use of the composite score (e.g., Teasdale & Jennett, 1976).

Chadwick et al. (1981b) noted that those tests or subtests in a neuropsychological battery most likely to show impairment had in common the fact that successful performance was quite heavily dependent upon a patient's ability to respond quickly, and they involved visuo-motor and visuo-spatial skills. Winogron and co-workers supported the hypothesis that speed of performance is sacrificed following head injury. They examined a broad range of neuropsychological functions in a sample of head injured children whose injuries varied in severity from mild to severe. The mildly-injured patients showed no loss of consciousness (LOC) or LOC less than 20 minutes; the moderately-injured had LOC longer than 20 minutes, or, skull fracture with contusion or haemorrhage or neurologic signs or EEG abnormality; the severely-injured required intracranial pressure (ICP) monitoring as part of the neurosurgical treatment for head injury.

Results indicated that the test measures which showed differential deficits across severity groups were all timed

tests (finger tapping test, Tactual Performance Test, The Grooved Pegboard Test, fluency test, WISC-R Performance subtests), whereas among those subtests not showing such "dose-response" relationships, only two incorporated timing into their scoring procedures. Bawden, Knights and Winogron (1984) further reported that the severely head-injured children who showed deficits on tests requiring motor speed and motor speed plus visual-spatial skills, did not show generalized deficits on either motor or visual-spatial abilities. This finding strengthens the argument that speed of performance was the principally affected dimension.

Winogron et al. (1984), in addition to comparing the test performances of the three severity groups, also examined the relationships between individual neurologic indices of injury severity and neuropsychological outcome. Their findings were promising. Deficit index (DI) scores, which are summary measures of the percentage of psychological test scores two or more standard deviations below the normative mean, were related to a number of neurologic indices. Those patients who were classified as severely abnormal on the DI at one year post-trauma (having scored two standard deviations below the mean on at least one-third of all tests administered) had severe GCS ratings at hospital admission, indicating severe or "deep" coma more frequently than those with more optimistic DI scores. Their injuries were more frequently rated severe in terms of overall neurologic severity, they were more likely to have CT Scan abnormalities, and there was a tendency for more of them to

have EEG abnormalities.

Winogron et al. (1984) investigated possible relationships between acute intracranial pressure (ICP), an important cause of secondary brain damage after head injury (Ivan, Choo, & Ventureyra, 1980), and subsequent psychological deficits. They found no relationships. Significant correlations between coma measures (duration of unconsciousness and depth of coma) on the one hand, and neuropsychological test scores on the other, were found for at least one measure of every major neuropsychological function.

To summarize, neuropsychological deficits (not including intellectual deficits) are common after head injury, particularly severe head injury. Timed visuo-spatial and particularly visuo-motor tasks are particularly sensitive to the effects of head injury in that they usefully discriminate between different severities of trauma. Coma "depth" and duration are inversely related to particular neuropsychological abilities. Neuropsychological recovery, which may be slower than neurologic recovery, is maximal during the first year post-trauma.

(II) Reaction Time Following Head Injury~

(1) Definition and Introduction

Reaction time (RT) can be defined most generally as the time taken by a person to react or respond to a stimulus. More

specifically, it is the time between the onset of a stimulus (defined operationally) and the initiation of an appropriate predetermined response (defined operationally).

There is an important assumption generally made in RT research (Pachella, 1974) that RT represents the minimal amount of time required by a subject to produce a correct response for the particular stimulus presented. Because the speed and accuracy of responses are determined to some extent by experimental instructions, very fast responses ("anticipations") and very slow responses are often "edited out" of the obtained data by researchers. This procedure is not without its critics, and attempts have been made to develop techniques to circumvent the problem (Kornblum, 1973; Ollman & Billington, 1972). Nevertheless, this "editing" procedure does shape the definition of RT. Also, RTs for error responses are typically excluded from analyses (although times for incorrect responses are sometimes examined independently to help determine how Ss adopt a compromise or "tradeoff" between speed and accuracy when responding--see below).

RT data are typically derived from one of two classes of RT paradigm--a simple RT paradigm, or a choice RT paradigm. The usual simple RT paradigm, although superficially simple, consists of a warning stimulus (WS), one or more foreperiods (FPs), a reaction stimulus (RS) (sometimes called the imperative stimulus), a response (R), and an intertrial interval (ITI) (e.g., Niemi & Naatanen, 1981). The usual choice RT paradigm consists of these same factors, but has more than one

reaction stimulus (RS) and more than one response (R) possibility per trial. Each of these variables can vary along several dimensions and it is known that RT is affected by the complex interactions of these factors.

The RS (reaction stimulus) is the predetermined stimulus to which a subject (S) will make an R (response). The WS (warning stimulus) precedes the RS (reaction stimulus) and is intended to alert the S to the imminent RS. The period of time elapsed between the WS and the RS is the FP (foreperiod), and the time elapsed between an R and a subsequent WS is the ITI (inter-trial interval).

The use of RT measures for the investigation of psychological phenomena in normal and patient populations has a long history in experimental psychology (see Blackburn & Benton, 1955; Boring, 1957). In recent years the resurgent interest in human cognitive functioning, or "information processing" has led to an increasing, if sometimes uncritical, use of RT techniques.

Studies employing RT measures can generally be divided into two distinct categories (Pachella, 1974; Niemi & Naatanen, 1981). In the first category are studies which have used RT as a dependent variable for the study of various mental processes. Researchers conducting this type of study have frequently used a theoretical model of the particular process of interest to generate predictions concerning its duration (or the duration of some subcomponent of the process) (Pachella, 1974). In such studies, RT is used as a tool for the understanding of substantive psychological issues.

In the second category are studies examining the response process or RT per se. These studies, which have been concerned with methodologic issues, have used systematic parameter manipulations to "account for variations in reaction time without regard for specific experimental paradigms and substantive problems" (Pachella, 1974, p. 42).

The current research employs RT as a dependent variable in the study of differences in information processing and response strategies between head-injured children and normal controls. It therefore falls into the first category of RT studies. However, knowledge derived from the second type of RT study, that pertaining to RT per se, will be integrated into this research, arguably to a greater extent than has been done in previous studies of head-injured patients.

(ii) Reaction Time After Head Injury: A Review of the Literature

The literature on RT after head injury is quite limited, particularly with respect to children's head injuries. The adult studies are reviewed first, and then data pertaining to pediatric head injury are discussed.

RT measures were first used to evaluate the effects of head injury in adults 40 years ago. Reusch (1944) administered a simple visual RT task to acutely head-injured patients (n=25), patients suffering the chronic effects of head trauma (n=32), and to a group of controls (n=25). The severity of the injuries was not reported for either patient group, and the average

injury-test interval was not specified. Also, the patients were, on average, more than 17 years older than the controls. The data from this early study showed that both clinical groups, which did not differ from each other, were significantly slower than the controls. The methodological shortcomings of the Reusch (1944) report obviously limit the usefulness of these findings.

Dencker and Lofving (1958) on the other hand, did not find significant slowing on simple visual or auditory RT tasks for 27 mild closed head injury patients relative to their non-injured monozygotic twins an average of ten years post-trauma. This lack of differences may be attributable to the mildness of the injuries sustained (the majority of patients had PTA less than or equal to one hour) or to recovery over time.

Virtually all subsequent studies of RT following adult head injury have employed "complex" or "choice" RT paradigms in addition to, or in lieu of, simple RT paradigms.

Norrman and Svahn (1961) found a group of severely head-injured patients (in coma at least one week) had normal stanine scores on a simple visual RT task two or more years post-trauma. Significant deficits were however revealed on a three-choice visual RT task.

Miller (1970) also found that a small group ($n=5$) of severely head-injured patients (PTA at least 1 week) were significantly slower on a choice visual RT task. In addition, a significant interaction between groups and task complexity (1-,

2-, 4-, and 8-choice tasks were used) revealed that the magnitude of group differences increased with the number of stimulus-response alternatives.

Results opposite to those of Norrman and Svahn (1961) and Miller (1970) were however reported by Klensch (1973). Klensch found that simple auditory and visual RT task discriminated between a mild head injury group ($n=76$) and a control group at some unspecified duration post-injury, whereas an intermodal choice RT tasks did not. Van Zomeren (1981) has offered two possible explanations for this unexpected and unusual finding. First, fundamental differences between the simple and complex tasks, such as the requirement on the complex task that Ss not respond to particular stimulus combinations, may have elicited different response strategies from Ss thereby masking group differences. Secondly, the argument was made that Ss may have sacrificed speed to attain a higher level of accuracy in the choice condition. Klensch did not examine speed-accuracy tradeoffs, therefore this question cannot be answered.

Testing a group of 12 mildly-injured Ss (PTA less than 1 hour) within 24 hours of their trauma, Gronwall and Sampson (1974) also failed to find significant slowness relative to normal controls on a choice visual RT task (with 2, 4, 6, 8, or 10 stimulus-response alternatives). They did however, discriminate between groups with a more complex "symbolic" or "non-compatible" choice RT task, which had low stimulus-response compatibility. A nonparametric analysis revealed a significant interaction between group membership and the number

of alternatives in the "symbolic" choice task. This finding of increasing group differences with increasing task complexity is consistent with the findings of Norrman and Svahn (1961) and Miller (1970). These findings are also supported by the research of Van Zomerén (Van Zomerén, 1981; Van Zomerén & Deelman, 1976; 1978) discussed presently.

Van Zomerén's doctoral dissertation consisted, in part, of a number of studies examining RT in head injured adults. In the first of these studies, Van Zomerén and Deelman (1976) compared the effectiveness of a simple RT task and four complex RT tasks for discriminating between head-injured Ss (coma at least one-half hour, average injury-test interval (ITI) 108 days) and matched controls. The choice RT tasks involved two or four stimulus-response combinations and required either unilateral or bilateral responses. Results showed that the head-injured Ss were slower on all five tasks, and a significant interaction between groups and complexity on the unimanual tasks revealed that head-injured Ss were particularly hindered by the complex tasks.

In a second experiment reported by Van Zomerén and Deelman (1976) it was found that head injury severity and task complexity interact significantly in their effects on RT. Severely-injured Ss (in coma longer than 1 week), tested three to six months post-trauma, showed marked increases in RT for a four-choice unimanual task relative to a simple RT task. This same finding was confirmed in a repetition of the second experiment conducted more than 22 months post-trauma (average

ITI=669 days). A subsequent re-analysis of the data for experiment one (Van Zomeren, 1981) comparing the two-choice RT task and a comparable (motorically equivalent) portion of the four-choice RT task also confirmed the significant interaction between injury severity and task complexity, while controlling for the motoric requirements of the tasks).

Van Zomeren and Deelman (1978) examined the course of recovery on simple and choice RT tasks by testing adult Ss at five weeks, ten weeks, and five months post-trauma, and then three times in the middle of each successive half year. Patients in this study were classified as mildly injured (coma less than 1 hour), moderately injured (coma of 1 hour to 1 week), or severely injured (coma longer than 1 week). Analyses of the data revealed three significant interactions. Injury severity and task complexity interacted, with the severely-injured group showing the greatest speed decrements on the more complex tasks. Also, injury severity and ITI interacted significantly with the mild, moderate, and severe HI groups showing progressively greater recovery across testings. The significant interaction between task complexity and ITI indicates that recovery curves for choice and simple RT tasks were different, with recovery on the choice task continuing for a longer period of time.

In Van Zomeren's 1981 dissertation he attempted to determine whether slowed decision-making processes or slowed motor responses were responsible for the often observed slowing after head injury. To separate-out decision time (DT) and movement

time. (MT) he required Ss (adults) to depress a "home" key until stimulus onset and then to press a response key at the time of stimulus presentation. Van Zomeren assumed that the time between stimulus onset and disengagement from the resting or "home" key was the DT, and that the time between disengagement and pressing of the response key was the MT. The sample for this study consisted of eight severely-injured Ss (PTA of 7-124 days) who were tested with both a simple and a four-choice visual RT task between six weeks and six months post-trauma.

Only responses for one of the four response alternatives in the four-choice task were analysed in order to control for the motoric requirements of the simple and choice RT tasks. Results for the DT analyses revealed a significant interaction between groups (head-injured and control) and task complexity, with head-injured Ss showing larger deficits on the complex task. MT results did not show an interaction, but task complexity did significantly effect MT. Although Van Zomeren argued that these results indicate that prolonged decision times account for the slowed performances of head-injured adults, the finding of longer MTs for both groups on the more complex task should lead one to question the validity of the MT as a measure of purely motoric differences between groups. It is important to state that the validity of using the above procedure to separate decision-making time from motor movement time was not established by Van Zomeren, and it appears to constitute a rather naive approach to the problem. There is not sufficient reason to assume that movement towards a goal is begun only

34

after all relevant information processing has been completed, nor that these two components of the reaction process can be so readily partialled out.

(iii) RT in Pediatric Samples

Only two studies were found which used RT tasks to evaluate head-injured children. Levin and Eisenberg (1979) administered a simple RT task and two-choice and four-choice visual RT tasks to a group of 42 adolescents after a median median-test interval ITI of 19 days (range 1-185 days). They used the RT tasks as part of a battery of tests to assess major neuropsychological functions, and did not evaluate the RT results in any detail. Nevertheless, they reported that 22 per cent of their sample was impaired on one or more of the tasks (two or more standard deviations below the normative mean) although the incidence of impairment was not systematically related to injury severity.

In the only other study located (Chadwick, Rutter, Shaffer, & Shrout, 1981), a two choice RT task and the comparable (motorically equivalent) part of a four-choice task were administered to severely head-injured children (PTA between 1 week and 3 months) two and one-quarter years post-trauma. The tasks, comparable to those of Gronwall and Sampson (1974), were "non-symbolic" and "symbolic" meaning there was high stimulus response compatibility in the former condition, and a rearrangement of these stimulus-response pairings in the latter condition. In all four conditions, results indicated that the impairments for the head-injured Ss were non-significant.

However, a sub-analysis of 8 Ss who had initially suffered intellectual impairment but who no longer showed it at one year follow-up revealed that RT was the only measure which differentiated head-injured Ss from controls.

(iv) Summary and Evaluation of Studies to Date and Goals of Current Research

Studies investigating RT in head-injured adults have, to date, established a number of empirical findings. First, it has been demonstrated that head-injured patients generally do have significantly longer RTs on simple RT tasks. Second, they have been shown on several occasions to take longer on choice RT tasks, which require the pairing of a predetermined response with each of two or more stimulus possibilities. Third, a "complexity" effect has been demonstrated, which is to say that differences between head-injured and non head-injured groups are generally larger as the complexity of the RT task increases. Fourth, the effects of head injury severity on RT have been quantified, with severely-injured Ss generally showing greater slowing than mildly- or moderately-injured Ss, at least on choice RT tasks. Fifth, the deficits in speed of responding have been shown to last for considerable periods of time after trauma, with severely-injured Ss still showing significant choice RT deficits at two years or more post-trauma.

Because only two studies employing experimental RT techniques with head-injured children have been published, considerably less is known about slowed post-traumatic

performance in this population. Knowledge of the effects of head injury on pediatric RT are in fact meagre. Levin and Eisenberg (1979), who reported only minimal analyses of their data, found that about one-fifth of patients were impaired. They did not however specify whether deficits occurred on simple or choice RT tasks.

Chadwick et al. (1981), in a more completely reported study, failed to discriminate between head-injured and non head-injured children with choice RT tasks. They did however find significant deficits among a sub-sample of Ss who had initially shown intellectual impairment, but who had since recovered.

Differences in the injury-test intervals and in the RT tasks used in these studies, and differences in the severity of head injuries across these samples, makes a meaningful comparison of the obtained results difficult. All findings concerning RT in head-injured children may be considered equivocal, and the information which has emerged from studies of adult RTs following head injury cannot be generalized to pediatric populations without further empirical support.

The Current Research

The effects of head injury on simple and choice RT are empirically investigated. It was logical to assume, on the basis of the adult studies reviewed above, that head injury severity, task complexity, and time elapsed since injury would be important determinants of the relation between head injury and RT in children. The present study examines the effects of

manipulation of these parameters on mean and median RTs (medians are often used in RT research because of the known positive skew of RT distributions; Pachella, 1974).

Aside from the measures of central tendency, other dependent measures of interest are the variance and the skew of the RT distributions. Previous studies of head-injured adults and children have disregarded these second and third moment statistics, potentially sacrificing much information. It is conceivable that for a given task the distributions of RTs for head-injured and control groups have similar means, but that patients show more intra-subject variability than do controls. If patients do show greater intra-subject variability, this would indicate that they are less efficient in predicting and rapidly responding to the onsets of stimuli.

Examination of the skewedness of RT distributions is also potentially informative. Positive skew in RT distributions may in some cases (McCormack & Wright, 1964) reflect inhibited anticipations. This means that Ss have begun to respond to a stimulus prior to its occurrence, have stopped the response, and then resumed it again. The result is an occasionally prolonged RT. It is reasonable to expect, for reasons elaborated below, that head-injured Ss would be unsure of their abilities and may therefore adopt such conservative response strategies.

As well as summary statistics, the functional relations between foreperiod (FP) and the mean, variance and skew of RT distributions are all of considerable importance when FPs vary across trials or across blocks of trials.

In an RT task with a rectangular distribution of FPs (in which the probability of occurrence of each FP at the onset of a trial is equal), the relation between RT and FP is typically monotone declining, though the function reaches asymptote at longer FPs. There are a number of theoretical explanations of this relation between FP and RT (see Niemi & Naatanen, 1981). Among them is the fact that the probability of immediate occurrence of a stimulus, given that it has not yet occurred (the "conditional probability"), increases with the time elapsed since the WS. This means that the subject's expectancy that a signal will be presented (immediately) increases as the FP increases, therefore, the likelihood of a rapid response increases as FP increases.

It may be that head-injured children do not learn the temporal characteristics of a simple RT task with variable FPs as efficiently as do the normal controls. In other words, RT is expected to decline less rapidly as a function of FP for the head-injured group than for the control group. Another possibility is that the data for head-injured Ss may show extreme violations of monotonicity reflecting greater intra-subject response time variability.)

As was mentioned above, the assumption is generally made in RT studies that an RT represents the shortest time required by an S to produce a correct response. However, in practice, Ss almost never respond at a rate which produces zero errors on a choice RT task. Therefore, RTs and error rates typically represent a compromise between the demands for maximal speed and maximal accuracy (Wood & Jennings, 1976). Very little is in fact known about the response strategies (or "speed-accuracy

tradeoffs") of normal children on RT tasks or any tasks requiring speeded responses.

Virtually nothing is known about the response strategies of children with acquired brain damage following head injury. There is, however, good reason to predict that brain-damaged children who have survived a head injury may have altered feelings of confidence concerning their own intellectual abilities. Numerous neuropsychological studies (see above) have demonstrated that both adults and children show a wide range of deficits following head injury, particularly within the first year to two years post-trauma. Ss may become aware of these handicaps and adjust their response criteria to be more conservative. Specifically, they may sacrifice or "trade" speed of response in order to attain a higher level of accuracy.

One method of examining speed-accuracy tradeoff strategies (several methods are available; two are used in the current research) is to compare response latencies for correct responses and incorrect responses on a choice RT task (Swenson, 1972; Jones & Duffy, 1982; Vickers, 1979). Swenson (1972) has shown that for Ss who emphasize speed over accuracy, errors tend to be faster than correct responses. Conversely, correct responses tend to be faster than errors for Ss who favour accuracy over speed. Similarly, Jones and Duffy (1982) found that for normal Ss classified as "reflective", mean RT for correct responses on a choice RT task was shorter than mean RT for incorrect answers. If head-injured Ss are conservative (or "reflective") responders, the same relation between RTs for correct and incorrect responses should be found for this group.

Reports of analyses comparing RTs for correct and incorrect answers were not found in either the adult or pediatric head injury literatures. The likely reason is that most researchers employing RT paradigms simply discard error responses, which they consider to be part of normal variability (Pachella, 1974, p. 60). This reasoning is faulty because, in Pachella's words "small differences in error rate can lead to large differences in RT" (Pachella, 1974, p. 60; see also Wood & Jennings, 1976, p. 92), especially on RT tasks where Ss normally have high overall levels of accuracy.

Another reason why such analyses have been impossible is the fact that most researchers have used RT tasks on which Ss, even brain damaged Ss, make virtually no errors. The choice RT tasks used have typically just been extensions of the simple RT paradigm, i.e., Ss are faced with two or more stimulus lights illuminated one at a time, and are required to press a button corresponding to the stimulus.

Line length discrimination tasks have been useful for examining speed-accuracy strategies in adults (Link & Tindall, 1971; Swenson, 1973) and in normal children (e.g., Jones & Duffy, 1982). These tasks require more complex cognitive processing than the typical choice RT task described above, therefore Ss commit errors on them more frequently. A line length discrimination task is being employed in the current research to examine speed accuracy trade-offs. The use of this task in combination with response criterion times (CTs or

"deadlines"), requiring Ss to respond within predetermined time periods, will also be attempted. This deadline procedure experimentally "manipulates" subjects speed-accuracy criteria systematically over a wide range" (Wood & Jennings, 1976, p. 94) by employing several different speed-emphasis conditions.

Because of the relative laxity of the assumptions required by this procedure (assumptions that response criteria differ systematically across speed-emphasis conditions, and that mean speed and accuracy values in each of these conditions are acceptable summaries of the speed-accuracy distribution for that condition), and the ease of computation, and because it is less sensitive to variability in Ss speed-accuracy criteria, Wood and Jennings (1976) have judged it to be the best method for determining speed-accuracy tradeoff functions.

The addition of CTs to the task also allows a comparison of the performances of head-injured Ss on relatively open-ended (line discrimination without CTs) and relatively structured tasks (line discrimination with CTs) and an examination of the issue of whether head-injured Ss are capable of altering their response strategies because of the imposition of time limits on a task.

A final issue discussed here concerns the methodologic shortcomings of previous RT studies with head-injured Ss. Many studies reviewed above have used a poor or inadequately described classification system to identify the severity of the head injuries sustained in their samples. This practice has made inter-study comparisons difficult and has obscured the

relationship between injury severity and extent of RT slowing. The current research employs a proven system of head injury classification (see Winogron et al., 1984) which has been shown to relate significantly to a number of neuropsychological outcome measures after head injury.

Variables which influence, or might possibly influence, RT such as age, injury severity, and time since injury are controlled for in this study, or employed as covariates in analyses of the obtained data.

Because Ss in this study were recruited through the neuropsychology service of the CHEO, neuropsychological test data were available for all the patients. While the ages of the Ss, their physical injuries, and their intellectual abilities determined which tests were administered to them, some tests were administered to virtually all those included. The relation of certain of these neuropsychological test scores (the tests are described by Knights & Norwood, 1979) to the data obtained in the current study were undertaken. An important limiting factor for such an analysis is the lack of uniformity in the interval between neuropsychological testing and RT testing.

(III) Statement of Research Hypotheses

It was hypothesized that:

(1) Head-injured Ss will, on average, be significantly slower than controls on a simple RT task, and their performances will show significantly greater intra-subject variability.

(2) The distribution of RTs on a simple RT task will be significantly more positively skewed for head-injured Ss than controls, suggesting a greater incidence of inhibited anticipations among the brain-injured.

(3) For control Ss, intra-subject variability will decrease significantly as a function of FP duration on a variable FP, simple RT task. The decreasing variability will reflect improved prediction of stimulus onset as a function of FP. The variability will not decrease significantly for head-injured Ss.

(4) Data for head-injured Ss on a variable-FP, simple RT task may not show the normal monotone decreasing relationship between FP and RT. Data for control Ss will show this relationship.

(5) Head-injured Ss will, on average, be significantly slower, but not significantly less accurate, than controls on a choice RT task involving line length discrimination, and their performances will show significantly greater intra-subject variability.

(6) Average RT, intra-subject variability in RT, and the positive skew of RT distributions, will all be significantly related to head injury severity, with the severely-injured, mildly-injured, and control groups showing progressively faster and less variable responses, with fewer inhibited anticipations.

(7) When a "ceiling" (allowable maximum) is imposed on RT by the introduction of criterion times to a choice RT task, head-injured Ss will be able to shorten their average RTs without substantially sacrificing accuracy.

(8) The slope of the speed-accuracy tradeoff function (SATF), which reflects the amount of increase in response accuracy for each unit increase in RT, will be greater for control Ss than head-injured Ss.

(IV) GENERAL DESCRIPTION OF EXPERIMENTS

Experimental Tasks

All participants took part in Experiments I, II and III in that order. The rationale for the experiments is described in the "Current Research" section beginning on page 36. In Experiment I, a simple visual RT task was administered. This task required subjects, on each trial, to remove their fingers from a resting key and to push a response button as quickly as possible following the onset of a computer-generated stimulus. Experiment II employed a choice RT task. It also involved a rest button procedure, but required subjects to decide which of two line stimuli was longer and to push one of two response buttons to indicate their choice. Experiment III involved the same experimental task as Experiment II, modified to include response deadlines and instant feedback concerning the speed and accuracy of responses.

Subjects

This study consisted of three experiments which evaluated three groups of children; two groups composed of head-injured patients (mild and severe), and a control group. Those in the patient groups were between the ages of five and sixteen years at the time of their injuries. The control group was matched as closely as possible for age and sex to the two patient groups.

The head-injured Sa were 29 children who received treatment for blunt head injuries at the Children's Hospital of Eastern Ontario (CHEO) in Ottawa, Canada, or were transferred to CHEO for evaluation and/or continued treatment. All patients were

recruited through the neuropsychology program of the CHEO psychology department. An attempt was made to exclude from this study all patients with premorbid histories that included neurologic, behavioural or psychiatric/psychological disorders brought to the attention of health practitioners. Also excluded were Ss who had fine or gross motor deficits on the dominant body side, or visual impairments not correctable by glasses. The exclusion of Ss was based on data from CHEO medical records and notes from parental interviews made at the time of initial neuropsychological assessment.

Group One: Severe Head Injury

Assignment to this group was based on the neurologic severity of the injury sustained. The 15 severely-injured patients included were those who at the time of initial hospitalization (at CHEO or elsewhere) had scores of seven points or less (of a possible 15, which indicates normal consciousness) on the Glasgow Coma Scale (GCS) a standardized scale for the assessment of the "depth" or severity of impaired consciousness (Teasdale & Jennett, 1974). This scale is presented in Appendix One. The GCS is easy to use (Teasdale, Jennett & Knill-Jones, 1974) and can be used retrospectively. It has good inter-rater reliability (Teasdale et al., 1974) and internal consistency (Levin & Eisenberg, 1979), and scores on the scale are related to medical outcome after head injury (e.g., Ivan et al., 1980; Jennett et al., 1977). Its increasing use allows the standardized assessment of injury severity.

47
The ratio of males to females in this group was 4:1, reflecting the greater incidence of head injury among male children (see Section 1:1). Ages of patients, at the time of injury ranged from 6.2 years to 10.9 years, and 9.4 years to 11.8 years at the time of reaction time testing. Injury-test intervals ranged from 3 months to 49 months and averaged 24.7 months.

Treatments for the patients in this group consisted of continuous ICP monitoring and the related neurosurgical maintenance procedures including therapeutic barbiturate coma (see Ivan et al., 1980). There currently exist no methods for treating the primary mechanical effects of traumatic head injury. (Bruce et al., 1979). Medical maintenance is therefore aimed at preventing or reversing the deleterious secondary effects of brain insult, and at maximizing the conditions for early repair in the brain.

Elevated intracranial pressure (ICP) is associated with poor prognosis in cases of pediatric head injury (Troup, 1967; Vapalahti & Troup, 1971) and the continuous monitoring of ICP has proven to be extremely valuable in the management of patients in coma following severe head trauma.

The brain injuries sustained by the children in this group included edema, hematoma, contusion, and hemorrhage. What all the children in this group had in common, in addition to depressed GCS scores, was elevated ICP, which required the above-mentioned monitoring and treatment regimens. These regimens are very briefly described here to characterize the

nature and severity of the changes undergone by the brains of these patients. The management regime is as follows: in the absence of operable lesions, a fiberoptic pressure transducer is placed epidurally in the right frontal area of the cranium, providing a continuous digital display of ICP on an accompanying monitor (Ladd Intracranial Pressure Monitor, Roche Medical Electronics). Such monitoring is used in conjunction with artificial respiration and administration of drugs to treat or prevent edema, ischemia, and elevated pressure. The goal of therapy is to reduce brain bulk and to reversibly suppress brain activity and metabolic functioning, thereby preventing or reversing the harmful secondary effects of brain insult. The mechanisms of the sensor and the technical advantages associated with its use have been described thoroughly (e.g., Ivan et al., 1980).

Group Two: Mild Head Injury

Assignment to this group was based on the neurologic severity of the injury sustained. Fourteen Ss were included in this group. Patients included were those who experienced no loss of consciousness post-trauma (GCS score = 15), or loss of consciousness lasting 20 minutes or less, with GCS scores of 8 or more. Presence of a linear skull fracture without a loss of consciousness was also considered mild, but presence of a depressed skull fracture excluded Ss from the mild group.

The ratio of males to females in this group was 11:3, reflecting the greater incidence of head injury among male

children. Ages of patients ranged from 8.3 to 14.4 years at the time of injury with an average of 10.7 years. At the time of testing, ages ranged from 8.6 to 16.6 years, with an average of 12.8 years. Injury-test intervals ranged from 9 months to 50 months, averaging 24.6 months.

Group Three: Controls

Control subjects were selected and tested prior to the testing of head-injured patients. This was done because controls would have been unavailable for testing throughout the summer vacation months, and because the equipment and computer programs were ready before official permission to begin testing had been received from the CHEO.

Control subjects were selected from Hopewell School of the Ottawa Board of Education. The children were selected from the first, third, fifth, seventh and eighth grades of the regular English and French immersion programs. Three boys and two girls were chosen from each class so that all persons selected from one grade were the same age - all first graders were between 6 and 7 years old, third graders were between 8 and 9 years, fifth graders were between 10 and 11 years, seventh graders were between 12 and 13 years, and all eighth graders were between 14 and 15 years. An attempt was made to choose Ss whose ages collectively covered the whole range of months.

If parental permission for participation were denied (about 10 cases) or if a child was repeatedly absent, a replacement child of the same sex and comparable age was tested in place of the

original. The average age at the time of testing was 12.7 years (standard deviation was 2.4 years).

No information other than age and sex was used to make decisions of inclusion or exclusion. Controls were subsequently matched to head-injured patients on the basis of age and sex only.

All control Ss were tested with the Finger Tapping Test (FTT: Reitan & Davison, 1974), commonly used in composite neuropsychological test batteries. On this test, Ss use their index fingers to depress a tapping key (one-quarter of an inch) as many times as possible within a specified time limit. Four 10-second periods were completed with each hand, and the child's score for each hand was the average of the best three of the four 10-second trials with each hand. This test of fine motor speed was chosen because it was included in the neuropsychological assessment for several of the head-injured patients.

The Peabody Picture Vocabulary Test-Revised (PPVT-R), Form L, an "individually administered, norm-referenced, wide-range, power test of hearing vocabulary (Dunn & Dunn, 1981, p. x) was administered to all controls. The purpose of the test was to provide a crude estimate of IQ. This test was selected because it is quickly and easily administered, and because it was included in neuropsychological assessment for several of the head-injured patients.

General Description of Groups

The causes of head injury in this research were typical. A greater number of patients were injured through motor vehicle/bicycle accidents, and a few were injured through falls (cf. Chadwick et al., 1981).

The ratio of males to females was 11:4 for the control group, 11:3 for the mild, and 4:1 for the severe groups. The ratios of right- to left-handers for the control, mild and severe groups were 15:0, 11:3 and 13:2.

The groups were balanced for age at the time at which they participated in this research, $F < 1$, $df = 2,41$, with average ages and standard deviations (in brackets) for the control, mild and severe groups being 12.7 years (2.4 years), 12.8 years (2.4 years), and 12.9 years (3.4 years) respectively.

Average ages at the time of injury did not differ significantly between the mildly head-injured (10.7 years, $SD = 2.4$ years) and severely head-injured groups (10.8 years, $SD = 3.3$ years), $F < 1$, $df = 1,27$. The difference in injury-test intervals for the two groups was also not significant, $F < 1$, $df = 1,27$, with average of 24.6 months ($SD = 17.2$ months) elapsing between injury and experimental participation for the mild group, and an average of 24.7 months ($SD = 13.8$) elapsing for the severe group.

All but two of the patients underwent three neuropsychological assessments. One patient in each of the head injury groups underwent only two neuropsychological follow-up assessments.

Intelligence (IQ) was assessed for the mild and severe brain injury groups soon after injury (during initial hospitalization, but after clearing of post-traumatic amnesia) and again an average of three and then nine months post-trauma. The WISC-R Verbal Performance and Full Scale IQs and standard deviations are presented in Table 1. These data were analyzed by three separate 2(group) x 3(testing) ANOVAs which revealed a trend for the main effect of group, $F = 3.64$, $df = 1,22$, $p < .07$, on Verbal IQ, and significant main effects for group on Performance IQ, ($F = 18.9$, $df = 1,21$, $p < .001$, and Full Scale IQ, $F = 7.26$, $df = 1,19$, $p < .05$. The findings of group differences in IQ are consistent with previous research (see Bawden et al., 1985) and confirm the neurologic definition of injury severity. Also, the main effect of testing was significant in each case: Verbal, $F = 7.41$, $df = 2,44$, $p < .01$, Performance, $F = 35.91$, $df = 2,42$, $p < .001$, and Full Scale IQs, $F = 24.22$, $df = 2,38$, $p < .001$. This result indicates improvements over time for all three IQ scores.

It is noteworthy that Kaufman (1979) has demonstrated that re-testing on the WISC-R within several months is expected to produce, in normal samples, increases averaging 3.5 points on Verbal IQ, 9.5 points on Performance IQ and 7.0 points on Full Scale IQ. While both head injury groups did show improvements across testings, these improvements rarely exceeded the normal expected increases minimally, or not at all. This suggests that the head-injured groups were not undergoing a period of rapid improvement, and that their performances were quite stable.

Table 1. WISC-R IQs for Head-Injured Groups Tested During In-Patient Status, and at 3 and 9 Months Post-Trauma

	Testing					
	1		2		3	
WISC-R Verbal						
(n=13) mild	99	(16)	104	(16)	103	(15)
(n=11) severe	82	(26)	87	(23)	92	(22)
WISC-R Performance						
(n=10) mild	103	(15)	115	(15)	120	(17)
(n=13) severe	75	(15)	91	(13)	101	(13)
WISC-R Full Scale						
(n=10) mild	101	(15)	107	(17)	112	(17)
(n=11) severe	78	(21)	88	(18)	96	(17)

Apparatus

The response board consisted of a sheet of 6 cm thick white plexiglass approximately 55 cm (width) x 50 cm (depth) with two sets of three vertically-aligned response buttons (one set for left handers, one for right handers). The upper surface of the plexiglass was 2 cm above the table or desk upon which it sat. Both sets of square, plastic response buttons (left and right) had a black "resting" button in centre, with identical red response buttons above and below the rest button. The buttons, which were 1.8 cm on all sides, were separated by 1.8 cm (between adjacent edges). The two sets of response buttons were 20 cm apart.

Stimuli appeared on an Electrohome brand video display terminal, model code V10-430, with a screen of about 28 cm. (height) x 36 cm. (width) which sat touching the front of the response board. All stimuli were generated by an Apple II plus microcomputer with custom made software.

Testing of patients was conducted without interruptions in an intern's office in the psychology department at CHEO. Controls were tested in a small room within their school. A portable sound barrier was used to "corner" the child in this room, obstructing the view of windows, and dampening hallway sounds.

(V) EXPERIMENT I

Purpose

The purpose of the first experiment was to administer a standardized, simple visual reaction time task, with the aid of a computer, to three well-defined, homogeneous groups of children in order to study the effects of head injury, both mild and severe, upon post-traumatic "information processing" abilities. Mild and severe head injury groups, and a control group matched (approximately) for age and sex (and in the case of the head injury groups, also matched for time since injury) were compared on mean and median reaction times, and the variance and skew of reaction time distributions in order that group similarities and differences in information processing could be assessed. The relation of these dependent variables to duration of foreperiod (or preparatory interval), were of critical interest. On a technical level, the use of a comfortable response apparatus with a "rest" key and automatic cancellation of trials on which premature responses were attempted was expected to yield uncontaminated data.

Procedure

Five practice trials and 125 stimulus trials were administered per S. For reasons listed below, stimulus trials were grouped into five blocks of 25 successive stimuli. The reaction stimulus (RS) on all trials was a white-colored square appearing in the centre of an Apple II plus video display terminal (VDT) until S responded (the stimulus was discontinued when a response was made). The warning stimulus (WS) was a

computer generated tone lasting about one-half second. An auditory WS was chosen to minimize confusion between the WS and the RS. A WS of moderate intensity was chosen because an increment in RT is known to accompany increasing WS intensity in studies where WS and RS are separated by a silent foreperiod (Kohfeld, 1969). Foreperiods were defined in this experiment as silent periods (without visual or auditory stimulation) beginning with the cessation of the WS and ending with the onset of RS. Foreperiods of 1, 2, 3, 4, and 5 sec. were equally represented and were randomly distributed within stimulus blocks (of 25 successive stimuli) in order to equalize fatigue effects across FP durations. This blocking of stimuli was also a safety measure in the sense that if some Ss had been unable to complete all 125 stimulus trials, due to fatigue or other reasons, equivalent data for each foreperiod would have been retained from completed trial blocks. In fact, all but one of the subjects did complete the entire five blocks of stimuli. A mechanical failure disrupted stimulus presentation for one subject, who was dropped from the analyses of Experiment I.

Each S received the same sequence of FPs to control for the known sequential effects of FP on RT (RT on trial x may be effected by FP on trial $x-1$; see Granjon & Reynard, 1977; Possamai, Granjon, Requin & Reynard, 1973).

While awaiting onset of the WS, S rested the index finger of his or her dominant hand on the "rest" at the centre of the response panel. In response to an RS, the finger was to be removed from the resting key and used to depress a red button

situated above the rest button. This response discontinued the RS. When the resting key was released before stimulus presentation, the response was considered an anticipation response, and was separately analysed. The time between a response and onset of the next WS (intertrial interval) was 1 sec.

The S was seated at a table facing the Apple II plus VDT and keyboard. Instructions for the S to follow throughout the task were presented visually on the VDT and were also read aloud by E. The instructions were as follows:

1. Please keep the finger you point with on the black button.
2. When you hear a 'beep' get ready, a white square is going to come on soon.
3. When the square comes on, push the red button above your finger as fast as you can.
4. After you press the red button then go back to the black button and wait for the next beep.
5. Remember, always use only your pointer finger.

To simplify instructions, particularly for the younger children, the experimenter stated that the index finger should remain on the rest button at all times except immediately following stimulus onset. If the children asked what would happen if they left the rest button before stimulus onset, they were told that the trial would not be counted.

Following presentation of instructions, S was asked whether he or she understood the instructions. When the task was understood, either immediately or following repeated instructions, five practice trials were administered. One

practice trial was administered for each of the five FPs. The 125 test trials were then administered.

RESULTS

Means and standard deviations not reported in this section are found in Appendix 19.

The dependent measures were: mean RT for each FP, and overall (with anticipated responses removed), median RT, within-subject variance (standard deviation), and skewedness. Each measure was analysed using a two-way repeated measures analysis of covariance (ANCOVA) with "group" as the between subjects factor, length of FP as the within subjects factor, and age (at the time of reaction time testing) as the covariate. Similar analyses were conducted for the brain damaged groups, with injury-test interval (ITI) as the covariate.

Age was introduced as a covariate in these analyses because despite the balance of groups on this variable, the age range of subjects in the study was considerable. There was reason to expect that RTs would be shorter for older children (see Pachella, 1974) and, in fact, this was the case. The correlations of age with overall RT for experiment one was $-.65$ for the control group, $-.63$ for the mild group, and $-.30$ for the severe group.

Injury-test interval was used as a covariate for the brain-damaged groups because there was also a great amount of within-group variability for this variable, and because the passage of time after trauma would be expected to coincide with spontaneous recovery for these groups (see introduction).

Mean RT

Mean RTs for each group are plotted as a function of FP in Figure 1. A detailed summary of a 3(group) x 5 (FP) repeated measures ANCOVA with covariate age is presented in Appendix 2. The main effect of FP was significant, $F = 44.00$, $df = 4, 160$, $p < .001$, as was the main effect for group, $F = 3.77$, $df = 2, 39$, $p < .05$. Post hoc comparisons using the Newman Keuls procedure revealed that overall RTs for the severely-injured group were significantly longer than for the control group. Significant differences were not found between the severe and mild, or mild and control groups. The interaction between FP and group did not approach significance, indicating that the functional relation between RT and FP is common to all groups. The effect of age as a covariate was significant as expected, $F = 12.46$, $df = 1, 39$, $p < .001$, indicating the importance of age as a determinant of speed of response.

In an analysis for the brain-damaged groups alone, a 2 (group) x 5 (FP) repeated measures ANCOVA with covariate injury-test interval (ITI) revealed a significant effect only for FP, $F = 33.87$, $df = 4, 104$, $p < .001$. A summary of this ANCOVA is found in Appendix 3.

The failure to find significant effects for ITI is likely attributable to the long ITIs in this study. Average ITIs for the mild and severe groups were 24.6 and 24.7 months respectively, whereas the opinion in the literature is that the bulk of recovery after head injury occurs in the first year post-trauma, particularly the first six months (Knights & Iven, 1984).

Figure 1: Mean Correct RT as a Function of Group and
Foreperiod

Exp 1 - Mean Correct RT as a Function
of Group and Foreperiod

Median RT

Because RT distributions tend to be positively skewed, the median RTs were also calculated in order to minimize the effects of extreme values.

Mean medians are plotted for each group as a function of FP in Figure 2. As with means, significant main effects were found for FP, $F = 47.39$, $df = 4, 160$, $p < .001$, and group, $F = 4.90$, $df = 2, 39$, $p < .05$. Newman Keuls comparisons did not reveal significant differences between any pair of group medians. No significant interaction between group and FP was found. The effect of age as a covariate was also significant, $F = 22.22$, $df = 1, 39$, $p < .001$ (see Appendix 4).

In an analysis of data for the brain damaged groups alone, a 2 (group) $\times$ 5 (FP) repeated measures ANCOVA with covariate ITI found a significant effect only for FP ($F = 34.45$, $df = 4, 104$, $p < .001$). These results were again comparable to the findings for mean RT (see Appendix 5).

Intra-subject Variability

The intra-subject variability in RT, or the standard deviation (SD) was included as a dependent measure because, as mentioned previously, SD is an indicator of the consistency with which a person can make rapid responses. While two or more group means may not differ significantly, it is possible that response rates are considerably more variable within one of the groups considered, reflecting an inadequacy of preparedness to respond. SD is plotted as a function of group and FP in Figure 3.

Figure 2: Median Correct RT as a Function of Group and Foreperiod

Exp 1 — Median Correct RT as a Function
of Group and Foreperiod

Figure 3: Intra-Subject RT Variability (SD) as a Function of
Group and Foreperiod

Exp 1 - Intra-Subject Variability (SD)
as a Function of Group and Foreperiod

ANCOVA results were similar to those reported for means and medians. Significant main effects were found for FP, $F = 8.57$, $df = 4, 160$, $p < .001$, and group, $F = 3.83$, $df = 2, 39$, $p < .05$, with no significant interaction. This indicates that the relation between FP and SD was common to all groups. Newman Keuls comparisons ($\alpha = .05$) failed to find significant differences between pairs of group means. Age emerged again as a significant covariate, $F = 9.89$, $df = 1, 39$, $p < .01$ (see Appendix 6 for details).

In the analysis of brain-damaged groups alone, a 2 (group) $\times$ 5 (FP) repeated measures ANCOVA with covariate ITI revealed significant main effects for FP, $F = 8.18$, $df = 4, 104$, $p < .001$, and group, $F = 4.85$, $df = 1, 25$, $p < .05$, with the severely-injured group showing more intra-subject variability (mean SD for severe group collapsed over FPs = 187.1; for mild group - 126.6) (see Appendix 7).

Skewedness

Analyses of skew data were included because it has been argued (McCormack & Wright, 1964) that positive skew of an RT distribution indicates the existence of stifled or inhibited anticipations. This suggestion is particularly relevant in light of the hypothesis that the groups differ in terms of response criteria. It is noteworthy that average skew for all three groups was always positively valued, possibly reflecting the existence of inhibited anticipations (McCormack & Wright, 1964). Skew is plotted as a function of FP and group in Figure 4.

Figure 4: Skewness of Correct RT Distributions as a Function
of Group and Foreperiod

Exp 1 - Skewness of Correct RT Distributions
as a Function of Group and Foreperiod

ANCOVAS of the skew data with covariate age for the three subject groups and with covariate ITI for the two head-injured groups revealed no significant main effects or interactions. The ANCOVA tables for these analyses are presented in Appendices 8 and 9 respectively.

Correlations

Correlations between IQs and measures of motor performance on the one hand, and overall average reaction times for all three experimental tasks on the other, are presented in Table 2.

DISCUSSION

The most fundamental finding in this first experiment was that of the same significant relation between FP and RT for all groups. RT was a monotone declining function of FP between 1 and 4 seconds, levelling off at 5 seconds.

RTs for the 2 sec FP were on average 87 msec faster than for a FP of 1 sec. An increase of FP to 3 sec brought about a further reduction of RT by an average of 54 msec, and an increase to a FP of 4 sec caused a further 29 msec reduction in RT. Only the increase of FP to 5 sec resulted in a reversal of this trend.

The finding that the longest RTs typically follow the shortest FP in a block of randomly varied FPs is in agreement with previous research findings (provided the range of FPs is not very narrow or very wide). Woodrow reported this finding as early as 1914 and it has been reported by several authors since that time (e.g.,

Table 2

Correlations of IQs and Motor Scores with Overall Average Reaction Times

		Neuropsychological Assessment			
		Early*		Late*	
	grp	RT (n)		RT (n)	
WISC-R(V)	m	-.19	(14)	-.31	(13)
	s	.16	(11)	.08	(13)
WISC-R(P)	m	-.22	(11)	-.11	(13)
	s	.23	(13)	-.35	(13)
WISC-R(FS)	m	-.32	(11)	-.25	(13)
	s	.20	(11)	-.06	(13)
PPVT(IQ)	c	-.46	(15)		
	m	.15	(9)	.76	(3)
	s	.73	(4)	-.35	(13)
TAPPING(dh)	c	-.60	(15)		
	m	-.13	(11)	-.05	(13)
	s	.07	(11)	-.21	(13)
MAZES(dh)					
	timer	-.44	(11)	.03	(13)
	s	.19	(8)	-.21	(13)
	counter	-.43	(11)	.03	(13)
	s	.27	(8)	-.23	(13)
HOLES(dh)					
	timer	-.46	(11)	-.16	(13)
	s	-.37	(6)	-.11	(13)
	counter	-.44	(11)	-.26	(13)
	s	-.45	(6)	-.28	(13)
PEGBOARD(dh)					
	time	-.48	(12)	-.12	(13)
	s	.46	(10)	.05	(13)
	error	-.43	(12)	.14	(13)
	s	-.18	(10)	.22	(13)

Abbreviations: V = Verbal; P = Performance; FS = Full Scale; grp = group; m = mild; s = severe, c = control; dh = dominant hand.
 *Early = inpatient, after clearing of post-traumatic amnesia.
 Late = average of 3 months post-trauma.

Gottsdanker & Way, 1966; Sanders, 1966). While the same effect has also been observed with a group of schizophrenics (Zahn, Rosenthal, & Skakow, 1963) it has not previously been demonstrated in a head-injured sample.

Reports in the literature (Baumeister & Joubert, 1969; Niemi, 1979) have shown that, for normal persons, RT decreases as a function of lengthening FP for short FPs, but is roughly constant for medium and longer duration FPs when presented, as in the present experiment, in a rectangular (equiprobable) distribution. The definition of 'medium' and 'longer' durations is variable and likely is influenced by the difficulty of the RT task. Baumeister and Joubert (1969) used FPs of 2, 4, 8 and 16 sec with four different distributions. For the rectangular distribution, RTs were about 10 to 12 msec longer for the 2 sec FP than for the 8 sec FP whereas average RTs for 8 and 16 sec FPs were virtually identical. Niemi (1979) who used FPs of .5, 1.0, 1.5, 2.0, 2.5 and 3.0 sec reported approximately asymptotic RT for FPs beyond about 2.5 sec.

Foreperiod in a simple RT task provides "the temporal frame of reference in which a subject prepares to respond to the RS [reaction stimulus] on a certain trial" (Niemi & Naatanen, 1981, p. 134). This means that a person's ability to accurately estimate FP length on a given trial determines his or her response readiness and therefore, presumably, response rate. Readiness to respond is presumably a function of one's level of expectancy (Naatanen & Merisalo, 1977), or the subjective probability of immediate onset of the RS, which is determined by one's time

uncertainty (Klemmer, 1956; 1957) about the RS.

The passage of time after onset of a WS increases the conditional probability of occurrence of the RS. As time passes, the immediate occurrence of the RS objectively becomes more probable, and readiness to respond to it is more likely to be immediately rewarded (Naatanen, 1970). This phenomenon accounts for the negative relation between FP and RT. The relation is, however, negatively accelerated and this negative acceleration is likely accounted for by the strong over-representation of medium FP lengths in Ss subjective experiences of FP. That is, medium and longer length FPs are experienced by Ss as comparable and thus yield comparable RTs (Naatanen & Merisalo, 1977).

Of particular relevance to the present study is the finding that there was no significant interaction between group membership (mild or severe injury or control group) and FP. This suggests that head-injured and non-head-injured children were dealing with, or processing, this probabilistic information in the same way. In short, mildly- and severely-injured children were quite capable of performing a complex task which required judgements concerning the passage of time and the probability of immediate stimulus occurrence.

A significant difference was found between RTs for the severe group and those for the control group. Subjects in the severely-injured group were slower on average by 80 msec, with the maximal group differences of 139 msec occurring at the shortest FP (1 sec).

As discussed earlier, slower RTs on simple RT tasks have

previously been reported for head-injured patients relative to normal controls. The earliest study (Reusch, 1944) reported that acutely head-injured adults were on average 80 per cent slower than controls at a simple visual RT task (540 msec vs. 300 msec). A "chronic" group suffering prolonged post-traumatic syndromes was 50 per cent slower (450 msec) than the control group. Reusch's failure to describe injury severity and injury-test interval unfortunately limits comparisons with these data.

A group of five severely-injured adults tested on simple and choice visual RT tasks by Miller (1970) was found to be about 23 percent slower on the simple task than a matched control group in the first year post-trauma (580 msec vs. 470 msec). An auditory WS preceded stimulus onset by "about 0.5 seconds" (p. 123), but no attempt to systematically vary FP was reported.

Klenach (1973) also found mildly head-injured patients were 19 percent slower than controls (256 msec vs. 216 msec) on a simple visual RT task, and 20 percent slower on a simple auditory RT task (213 msec vs. 171 msec). Both these differences were statistically significant, however, Klenach's (1973) report inadequately described injury severity and did not state warning interval duration or injury-test interval.

A slowing of simple visual RT by about 19 percent (700 msec vs. 590 msec) for brain damaged patients relative to normal controls was reported by Bruhn and Parsons (1971). These authors followed a heterogeneous group which included 8 head injuries (6 vascular trauma, 2 tumors, 4 "other") but did not

report data for this subgroup separately. No mention of a WS was made in this report.

VanZomerén and Deelman (1976) reported a series of three experiments with head-injured adults comparing simple and choice visual RTs at about 3, 5 and 22 months post-trauma (on average). The third experiment which examined only moderately- and severely- injured patients, an average of 22 months post-trauma, found no significant group differences in simple visual RT (294 msec vs. 303 msec). A later experiment by the same authors (Van Zomerén & Deelman, 1978) reported significant deficits of 8 percent for mild, 9 percent for moderate, and 17 percent for severe injury groups, relative to a control group at 2 years post-trauma. The results of this latter study (which is comparable to the current research in terms of injury-test interval and range of head injuries included) were close to those reported in the current research.

In summary, the bulk of evidence collected from head-injured patients is consistent with the findings reported here. Head injury does appear to slow responses on even a "simple" RT task. The present data reported add considerably to previous findings in the following ways. First, a relationship between head injury and simple RT has been established for the first time in a pediatric sample, with severely-injured patients slowing significantly relative to matched normal controls. Second, it has been shown that for controls and head-injured children; even those with neurologically severe injuries, RT on a simple RT task is related to FP. These patients are,

therefore, capable of completing a task which requires the understanding and use of probabilistic information. It was also shown that injury severity does not interact with foreperiod (or "preparatory interval") in effecting RT, suggesting that mildly- and severely-injured children used the probabilistic information in a similar manner.

Other parameters of RT examined here, but not in previous studies of head injury, have also shed some light on the issue of slowed responding after head injury. Intra-subject variability was included to assess the consistency with which members of each group could respond rapidly. Again the measure is functionally related to FP. Moreover, all three groups showed the greatest variability at the shortest (1 sec) FP. Overall, the severely head-injured group was significantly more variable than the mildly head-injured group, and examination of Figure 3 makes it clear that the greatest difference between groups occurs at the shortest FP.

Intra-subject variability of response rate may be considered an index of preparedness to respond. That is, the more efficiently one anticipates stimulus onset, and prepares to respond to this onset, the more consistent (less variable) will one's responses be. Response variability tended to decrease for all three groups as the preparatory interval increased (increasing the conditional probability of stimulus onset). Once again, the difference between groups is a difference of degree only. While the severely-injured were most variable, the functional relation between FP and RT variability was similar across groups.

The skew of the RT distributions of correct RTs was also measured because there is electromyographic evidence (McCormack & Wright, 1964) that the positive skew typical of simple RT distributions can be accounted for by "unobservable partial responding" (p. 43) occurring soon before or soon after stimulus onset. RT curves for all three groups were positively skewed, but skew did not differ for FPs or for groups. It is plausible, therefore, that these unobservable responses were occurring equally for all Ss, reflecting stifled anticipations and response uncertainty for all groups. The lack of differences among groups may be attributable to the experimental instructions. The experimenter supplemented the visually presented instructions with advice to the effect that Ss finger should remain on the rest button at all times except immediately following stimulus onset. In response to the often-asked question of "What will happen if I take my finger off the button before the square comes on", Ss were told that this behaviour would cause a cancellation of that trial.

The effects of age on RT were not of primary interest in this study. Nevertheless, age was used as a covariate in all ANCOVAs comparing the three groups because: (a) the within-group variability in age was considerable, (b) RTs of adults are known to be faster than those of children (e.g., Surwillo & Titus, 1976) and, (c) a nearly 3-fold difference in simple RTs has been reported (Surwillo, 1971) for normal children over an age span of 4-17 years.

The correlations of age and overall RT for experiment one in

this research were $-.65$, $-.63$, and $-.30$ for the control, mild and severe groups respectively. All ANCOVA analyses revealed significant effects for age as a covariate except the analysis of skew data, which revealed no significant effects whatsoever. These findings attest to the developmental improvements in RT and concur with previous findings. The substantially lower correlation for the severe group suggests that the importance of age as a determinant of RT is mitigated by the importance of other factors in this group. This is hardly surprising given the extent and complexity of the traumas sustained by these children.

The correlations of RT with WISC-R and PPVT-R intelligence scores and select scores from the Halstead-Reitan neuropsychological battery for children are presented in Table 2. It should be remembered that correlations on the left half of this table are correlations of RT scores and scores from the initial (inpatient) neuropsychological assessment, whereas correlations with the later neuropsychological assessment are found on the right side of Table 2.

The initial WISC-R scores were not correlated strongly with RT for the brain-damaged groups, suggesting that no simple relationship exists between post-traumatic intelligence measured soon after head injury and the ability to perceive and respond to stimulus onset. The finding of small but negative correlations for the mild group, and small but positive correlations for the severe group can be explained by the existence of an outlier in the severe group with very low post-

traumatic IQ and good RT performance.

Correlations between later WISC-R IQs and RT continue to be of small magnitude, and all are negative, as expected, except for one correlation between verbal IQ and RT for the severe group. These findings again confirm the finding that intelligence is not related in any simple fashion to speed on a simple RT task.

The PPVT-R was administered to all control Ss because (a) it is quick and easy to administer and yields an estimate of IQ, and (b) it was assumed that the records for the majority of head-injured patients would contain PPVT-R scores since this test is part of the neuropsychological test battery used at the CHEO.

Interpretation of correlations between PPVT-R IQs and RTs are complicated because (a) the PPVT (revised or original) was not administered to several head-injured patients at the CHEO and (b) existing forms (L and M) of the Peabody Vocabulary Test are not exactly equivalent to previous forms, and the differences between scores on the two forms are not consistent across the range of scores. Bearing these limitations in mind, it may be worthwhile to interpret only the data for the control group.

The finding of a moderately strong negative correlation between PPVT-R and RT suggests that intelligence, estimated from hearing vocabulary, is a moderately strong predictor of RT, accounting for approximately 21 percent of the variance in RT. While the Peabody IQ estimates leave a good deal of RT variance

unaccounted for, the correlations between WISC-R IQs and RT for brain-damaged Ss were considerably smaller. It is possible that IQ is more closely related to performance on RT tasks in normal controls than in children who have been head-injured.

Alternatively, the Peabody test may not provide a useful estimate of IQ in such a brain-damaged sample, particularly given the not infrequent evidence of language difficulties in head-injured populations (Levin et al., 1982) and the unknown course of recovery of these skills over time. A future study comparing head injured children with normal controls on the WISC-R, PPVT-R and simple RT should address this issue.

Four tests of motor function (described by Knights and Norwood, 1979) were also selected from the Halstead-Reitan battery to allow an assessment of the role of motoric disability in slowed RT performance. The tests were selected to assess fine and gross motor speed, steadiness and co-ordination.

The Tapping Test is a measure of fine motor speed which simply requires a child to depress a lever as rapidly as possible for a fixed period of time. The Mazes Test measures gross motor steadiness and control by requiring the S to move a stylus through a maze without touching the sides of the maze. The number of touches and their total duration are recorded electronically. The Holes or Progressive Holes Test, a measure of fine motor steadiness, requires a child to hold a stylus in the centre of a series of progressively smaller holes without touching the perimeter. The number and duration of touches are electronically recorded. The Pegboard Test measures eye-hand

coordination. Keyhole shaped pegs are placed into similarly-shaped holes and the speed and number of dropped pegs are recorded.

Correlations between RTs and scores on these motor tests administered soon after injury and again 3 months later (on average) are presented in Table 2. The Tapping Test, which measures fine motor speed, was administered to control Ss as well as head-injured patients. A moderate correlation was found between control group tapping scores and RT. This seems reasonable in light of the fact that the time taken to react to a stimulus onset must be affected by much more than simple speed of motor output. This test has poorer predictive power for brain-damaged children, particularly at the first neuropsychological testing, probably because tapping scores (and other measures of motor function) are effected by anti-convulsant medication, disorientation, excess fatigue and poor concentration, all of which are known to occur to varying degrees, during the early phase of post-traumatic recovery. This same explanation likely accounts for the weakness of correlations between the remaining motor measures and RT, although it is difficult to know whether these aspects of motor function, if measured accurately and reliably, would bear a stronger relation to RT performance.

82

(VI) EXPERIMENT II

The purpose of the second experiment was to administer a standardized, choice visual reaction time task to the head-injured and control children. The task selected was a relatively complex one which required comparisons of simultaneously presented line stimuli and rapid judgements of their relative length. This type of task was chosen to challenge all participating children - it was expected to be sufficiently difficult to require concentrated effort even from control children, but was not expected to be too taxing for the severely injured. Systematic manipulation of task difficulty was accomplished via the independent[1] manipulation of the ratios and differences of line lengths across stimulus presentations.

Experimental Task

A visual line length discrimination task was used. The task is a modified version of that used by Jones and Duffy (1982), which allows, in principle, not only the determination of differences in RTs between head-injured and control groups, but also measures of accuracy of response and the relation between speed and accuracy. There is clear evidence that with adults, RT varies with changing arithmetic relations between stimuli (differences and ratios on physical length) (Petrusic & Jamieson, 1979). Jones and Duffy (1982) have shown that normal children code both arithmetic relations (difference and ratio) with some degree of efficiency in terms of RT. In the Petrusic and Jamieson (1979) study, in which Sa

1. Although ratios and differences were independently manipulated, the overlap between lines may have caused ratios and differences to be confounded perceptually.

responses were virtually error free, RT was a monotone function of both the difference between line segments with ratio held constant, and the ratio between segments with differences held constant. In the Jones and Duffy study, although ratios and differences were to some degree confounded, RT was monotonically related to both differences and ratios. In short, relatively simple stimuli possess a rich arithmetic structure, and it is of considerable interest whether head-injured and control Ss code this structure with a similar degree of proficiency in terms of RT. In this experiment, stimuli were non-identical pairs of parallel horizontal lines, presented one above the other on a VDT of an Apple II plus computer. The stimulus pairs were generated from a 5 x 5 matrix in which the rows represent ratios of shorter to longer line lengths (.8, .825, .85, .875, .9) and the columns represent the differences between lines (.8 cm, .9 cm, 1.0 cm, 1.1 cm, and 1.2 cm). The stimulus pair on any trial was chosen at random from the 5 x 5 matrix of pairs with the proviso that each stimulus pair was represented equally often. Each cell in the matrix was repeated three times for a total of 75 trials. The width of all lines was 2 mm, and the distance between lines was fixed at 5 cm. Vertically, the top and bottom lines were 2.6 cm above and 2.6 cm below the center-point of the VDT. Horizontally, the center-point of the top line was always 1.0 cm to the left of center, and the bottom line was always 0.25 cm to the right of center. All Ss received stimuli in the same order. No time limit was imposed on stimulus presentations.

Procedure

The WS was the same as for Experiment 1. FP was fixed at 1.0 sec.

While awaiting onset of the WS, S rested the index finger of his or her dominant hand on a black "resting" button at the centre of the response board. On any item, S responded by pressing one of two red response buttons equidistant from the resting button. That is, if S chose the upper line to be longer, he or she moved their index finger from the resting button to a red-colored response button above the resting position. If the bottom line was judged to be longer, S was instructed to depress the red response button below the resting button which was the same distance from the resting button as the superior response button. Either response discontinued the RS. In all cases when the resting key was released before onset of RS, the response was considered an anticipation response and was separately analysed. The ITI or time between a response and onset of the next WS was 1.0 sec. No feedback was given to S during or after the experiment.

The S was seated at a table facing the Apple II plus VDT and keyboard. Instructions for the S to follow throughout the task were presented visually on the VDT and were also read aloud by E. The instructions were as follows:

1. Please keep the finger you point with on the black button.
2. When you hear a 'beep', this means two lines are going to come on the screen.
3. When you see the lines, decide which one is longer.

4. If you think the longer line is the one on top, push the red button above your finger. If you think the longer line is the one on the bottom, push the red button below your finger.

5. Be as fast as you can but make sure you don't make a mistake.

6. After you push one of the red buttons you can go back to the black button and wait for the next 'beep'.

Comparable instructions were provided for the French-speaking children.

Following presentation of the instructions, S was asked whether he or she understood the task. When the task was understood, either immediately or following repeated instructions, practice trials were administered. The test trials were then administered.

RESULTS

M Means and standard deviations not reported in this section are found in Appendix 19.

The dependent measures were mean RT, mean RT for correct responses alone (RTc), mean RT for error responses alone (RTe), and d' , an unbiased measure of accuracy of responding. Each measure was analysed using a one-way ANCOVA with group as the between subjects factor, and age as the covariate.

Mean RT

The ANCOVA (detailed summary in Appendix 10) revealed significant effects for the covariate age, $F = 20.92$, $df = 1,40$, $p < .001$, as well as for the main effect of group, $F = 5.79$, $df = 2,40$, $p < .01$. Newman Keuls comparisons revealed significant differences between the severe and control group means and between the severe and mild group means, $p < .05$. In both comparisons, the severe group was slower. The data are graphically presented in Figure 5.

Figure 5: Overall Mean RT as a Function of Group

Exp 2 - Overall Mean RT
as a Function of Group

The correlations between age and overall RT in this experiment were $-.70$, $-.56$, and $-.54$ for the control, mild and severe groups respectively.

RT Correct

The ANCOVA (Appendix 11) revealed significant main effects for age, $F = 20.59$, $df = 1,40$, $p < .001$, and for group, $F = 5.92$, $df = 2,40$, $p < .01$. Newman Keuls tests revealed significant differences between the severe and control groups, and the severe and mild groups $p < .05$. In both comparisons, the severe group was slower. The data are graphically presented in Figure 6.

RT Error

The ANCOVA revealed a significant main effect for the covariate age, $F = 8.94$, $df = 1,33$, $p < .01$, but no significant effect of group. The ANCOVA summary is presented in Appendix 12 and the data are plotted in Figure 6.

RT Correct versus RT Error

Relations between RTs for correct and error responses may indicate speed-accuracy tradeoff functions (Swensson, 1976) and were examined for all three groups. Results of the 3 (group) $\times$ 2 (correctness) ANCOVA (Appendix 13) with covariate age revealed significant main effects for group, $F = 4.14$, $df = 2,33$, $p < .05$, and the covariate age, $F = 12.91$, $df = 1,33$, $p < .01$, but no significant differences were found between correct and error RTs. Mean RTs and their standard deviations for correct and error responses are presented in Table 3.

The measure of accuracy was the signal detection index d' (see e.g., Green & Swets, 1966). In this case d' is a measure

2 OF 2

RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
1963-A
10X

Figure 6: Mean RT for Correct and Error Responses as a
Function of Group

Exp 2 - Mean RT for Correct and Error Responses
as a Function of Group

Table 3: Mean RTs and Standard Deviations for Correct and Error Responses

Group	Control	Mild	Severe
RT correct (SD)	771.4 (206)	920.2 (287)	1104.9 (320)
RT error (SD)	749.0 (429)	868.0 (453)	1078.8 (607)

of the subjects' discrimination accuracy independent of any bias to choose the top or bottom line as the longer of the two. Mean d' values are shown in Table 4. The ANCOVA (Appendix 14) revealed no significant main effects or interactions. In short, discrimination accuracy was statistically equivalent for the three groups though the severe group took longer to achieve the same accuracy.

Ratios and Differences of Line Length

The stimuli presented in Experiment II were pairs of horizontal lines. The actual difference between the lines was varied from presentation to presentation, as was the ratio of one line length to the other. Ratio and difference were selected from a 5x5 (ratio x difference) matrix which described all possible non-redundant combinations of the five ratios and five differences studied. The ratios employed were .8, .825, .85, .875, .9. The differences employed were .8 cm, .9 cm, 1.0 cm, 1.1 cm, 1.2 cm.

Data were analysed using multivariate analysis of variance (MANOVA). The between-subjects factor was injury severity (3) and the within-subjects factors were line ratio (5) and line difference (5).

MANOVA results using the Greenhouse-Geisser adjustment of degrees of freedom revealed a significant main effect of group, $F = 3.72$, $df = 2,41$, $p < .05$, and of difference, $F = 4.57$, $df = 4,133$, $p < .01$, though not of ratio, $F = 1.54$, $df = 3,120$, $p < .3$. No interactions were significant. A summary of MANOVA results is presented in Appendix 15. Mean correct RTs are

Table 4: Mean d' Values (and Standard Deviations)

Group	Control	Mild	Severe
d'	2.75	2.63	2.63
S.D.	(.41)	(.76)	(.44)

plotted as a function of group and difference in Figure 7.

DISCUSSION

The main finding in this second experiment is the significant difference between correct RTs for the severe head injury group and those for the mild head injury and control groups. Severely head-injured children in this experiment took an average of 1097 msec to decide without error which was the longer of the two simultaneously presented horizontal lines. Mildly head-injured children took an average of 918 msec, and the matched control group took an average of 821 msec. The mild group was 19 percent slower on average than the control group, and the severe group was 34 percent slower.

As noted, researchers have frequently compared choice RT tasks with simple RT tasks to test for a "complexity" effect. Norman and Svahn (1961), in one such study, found severely head-injured adults had abnormally low stanine scores on a visual 3-choice RT task, but not on a simple visual RT task, two years or more post-trauma. Miller (1970) extended this finding by demonstrating that differences between severely head-injured and control groups (in the first year post-trauma) became larger as an RT task became more complex. Miller used an apparatus which consisted of eight numbered response buttons arranged in a circle around a rest button. The number of response buttons to be potentially used on a trial was varied (Ss were informed of the possible responses) and Ss were required to push a button corresponding to a number flashed before them. As the number of

Figure 7: Mean Correct RT as a Function of Difference°
(in Line Lengths) and Group

Exp. 2. -- Mean Correct RT
as a Function of Difference and Group

response alternatives increased, so did the differences between groups.

A series of three experiments reported by Van Zomeren and Deelman (1976) helped to clarify the role of task complexity in post-traumatic RT deficits. The first experiment demonstrated that while head-injured adults and controls were slower on a choice RT task than a simple RT task (at 3 months post-trauma), head-injured patients were "disproportionately hindered" (p. 199) on the choice RT task. The second study showed that, between 3 and 6 months post-trauma, injury severity (coma duration) interacted significantly with task complexity (1- or 4-choice tasks), with the severely-injured patients (in coma at least one week) showing the greatest deficits on a 4-choice task. This interaction between injury severity and task complexity was re-affirmed in a third study in which patients were tested an average of 22 months post-trauma.

A longitudinal study by these authors (Van Zomeren & Deelman, 1978) compared simple and choice RTs for mild, moderate, and severe adult head injury patients at 6, 12, 18 and 24 months post-trauma. Three significant interactions were found. The group by complexity interaction confirmed the above results. The group by occasions interaction revealed that the slopes of the recovery curves differed according to injury severity, with the mild, moderate, and severe groups showing progressively greater improvements over time. An interaction between complexity and occasions reflected different recovery curves for simple and choice tasks with choice RT decreasing

until the sixth testing and simple RT flattening-out at the fourth testing.

While the above data indicate that choice RT tasks may be more sensitive to the effects of head injury than simple RT tasks, Klensch (1973) has reported the converse. He administered simple visual RT, simple auditory RT, and intermodal choice RT tasks to mildly head-injured patients. Significant differences between head-injured patients and controls emerged only on the simple task, with choice RTs for the head-injured (423 msec average) only 9 percent slower than for controls (387 msec average). Van Zomeren (1981) accounted for this atypical finding by arguing that Klensch's choice RT task was not a simple extension of the simple RT task. Klensch required Ss to respond to the pairing of a white light and a tone, but not to respond to other presentations of lights and/or sounds. While Van Zomeren's point regarding the discontinuity between tasks is correct, it is not at all clear why such a task with its inherent complexity should not elicit group differences in RT. The issue of task complexity and the resulting problems of interpretation are discussed below.

Another failure to find significant differences between mildly head-injured patients and controls was reported by Gronwall and Sampson (1974). Testing patients within one day of their injuries on 2-, 4-, 6- and 8- and 10-choice RT tasks, these authors found no significant group differences when stimuli and responses were located directly below like-numbered "alleys" in which a table-tennis ball appeared. In a non-

compatible condition, where alley numbers did not match response button numbers, significant group differences did emerge in the 8- and 10-choice conditions.

It is not the intention of the current research to compare the magnitude of group differences on simple and choice RT tasks. Nevertheless, some discussion of the nature of the differences between simple and choice tasks used here, and by other researchers, is appropriate.

A typical simple RT task, as described in Experiment I, requires a subject to traverse some distance between a resting position and a single response button in response to stimulation, typically the onset of a light. Choice RT tasks on the other hand, seem to be less easily characterized. Some choice RT paradigms (a) simply increase the number of stimulus lights and response buttons to some number greater than one, while (b) some paradigms require subjects to actually compare stimuli and make cognitive choices between two or more stimulus alternatives on the basis of some predetermined criterion. While it may be possible to argue that the former condition is simply a special case of the latter, it is clear that in practice, the experimental tasks are quite different, the latter being more complex.

Of the studies reviewed here only one (Klenach, 1973) deviated from the a-type paradigm. Klenach (reported in Van Zomeren, 1981) required Ss to respond to the pairing of white light and a tone, but to ignore a red light and tone, or an unpaired light or tone. Significant differences between head

injured and control groups were not found on this task. The study is difficult to interpret because Klenach did not publish in English and details must be taken from Van Zomeren's account of the study, and (b) the proportion of trials not requiring a response is not reported by Van Zomeren, and (c) Klenach did not adequately report the severity of injuries sustained (which Van Zomeren calls "mild") and (d) injury-test interval was also not reported.

It is tempting to assume that the negative results of this study result from the mildness of the injuries sustained, and the passage of time after injury. However, Klenach did find significant group differences on simple visual and auditory RT tasks. This unusual finding, therefore, remains unexplained.

In the current research, a line length discrimination task was chosen in order that Ss would be required to actively compare two stimuli, simultaneously presented, and to choose one of the two as correct. A relationship between stimuli had to be evaluated, and the difficulty of the discrimination was varied through variation of ratios and differences on line length. This is clearly a b-type paradigm. The task was found to be sufficiently sensitive to the effects of head injury to discriminate severities of injury. This was not true of the simple RT task used in Experiment I. Extent of impairment on a relatively complex discrimination task was, therefore, positively related to the severity of brain injury sustained. In current jargon, slowing of information processing was dependent upon the neurologic severity of injury.

The analysis of RTs for incorrect responses revealed no significant group differences. Error RTs were 10, 6 and 2 percent faster than correct RTs for the control, mild and severe groups respectively. These differences between correct and error RTs were, however, not statistically significant for any of the group comparisons. While the proportion of errors in this study was small, the statistical equivalence of error RTs across groups, and the lack of differences between correct and error RTs within groups, suggest that the three groups were processing information in the same way. The severe group was simply slower than the other two groups, irrespective of whether the response made was correct or incorrect. This conclusion is strengthened by examination of the unbiased measure of response accuracy, d' , which revealed that discrimination accuracy was the same for all groups, but simply took the severe group longer to achieve.

The effects of ratio and difference of line lengths on RT further confirms this conclusion. MANOVA results indicated that physical differences between line lengths were reasonably well coded by Ss. The smaller the difference between the lines the longer the RTs tended to be. Ratios, on the other hand, were not well coded. Importantly, there was no significant interaction between group membership and differences in line length, indicating that all Ss were sensitive to the physical differences in line length. Once again, these data support the notion that even severely head-injured patients can cope with a reasonably complex task with efficiency.

While comparable analyses have not previously been undertaken with any head-injured population, pediatric or adult, Jones and Duffy (1982) reported that even for pre-school children, RTs were related to stimulus difference and stimulus ratio. As differences between lines decreased, average RTs increased, also, as ratios depart from unity, average RTs increased. However, ratio coding was "relatively crude" (p. 204), and the relationship between RT and ratio showed "a number of violations of strict monotonicity" (p. 204). It may be that the use of a small range of ratios (.8 to .96 by Jones and .8 to .9 in this experiment) accounts for the findings described here. Research with adults has found that RT shortens significantly as ratios approach unity (Petrusic & Jamieson, 1979). However, Petrusic's stimuli were errorlessly discriminated triangle pairs with ratios of 1.178, 1.389 and 1.638. Differences in stimulus ratio, complexity, or discriminability may account for the disparate findings.

(VII) EXPERIMENT III

The third experiment is an elaboration of Experiment II. A visual line-length discrimination task was again administered with systematic variation of ratios and differences of line lengths. The task was changed to include criterion times and visual feedback. The imposition of three different criterion times, or response deadlines (2, 1.5, 1.0 sec.), and the addition of instant visual feedback concerning the acceptability of response speed and response accuracy after every trial were intended to generate speed-accuracy tradeoff functions for the three subject groups. The fundamental issue examined here was whether head-injured patients and controls could exploit the feedback provided to alter their response strategies in accordance with task demands.

Experimental Task and Procedure

The line length discrimination task used in Experiment II was again used here. Warning stimuli, response stimuli, and response procedures were exactly as described for Experiment II. This experiment differs from Experiment II in the following areas: (a) addition of response criterion times or "deadlines", (b) addition of feedback concerning accuracy of performance, and (c) instructions to Ss.

Response deadlines or criterion times (CTs) were used to generate speed-accuracy tradeoff functions (SATFs). An SATF defines the relationship between the speed and accuracy of

responses by manipulating Ss speed and accuracy criteria across a series of experimental conditions (e.g., Wood & Jennings, 1976; Pachella & Fisher, 1972). Three CTs were used: 1 sec, 1.5 sec, and 2 sec. Each CT was used in a separate block of 50 trials (each of the 25 stimulus pairs represented in the matrix in Experiment Two was presented two times for each CT condition). One-half of Ss in each group, chosen at random, received the CTs in order from longest to shortest, and the other half of each group received CTs in reverse order.

Each S was simultaneously informed, following each individual trial, whether or not his or her response was correct (YES or NO) and whether or not the response had been made in the allotted time period (SPEED O.K. or TOO SLOW) (Link, 1971). Feedback time was 3 sec maximum for all trials regardless of outcome, and the WS for the next trial was initiated 1 sec after Ss index finger returned to the resting position.

Instructions to Ss were:

1. In this game, you will decide which line is longer again.
2. But now you will have a time limit.
3. The computer will tell you if your answer was right and if it was fast enough.
4. Be as fast as you can but do not make mistakes!
5. Good luck!

As in the earlier experiment, comparable instructions were provided for the French-speaking children.

The following instructions were added between all stimulus blocks: "The amount of time you get to make an answer is now

going to change. It is important that you try to beat the clock while being as accurate as possible. The time limit will not change again until you are told."

RESULTS

Means and standard deviations not reported in this section are found in Appendix 19.

The central purpose of this experiment was to determine speed-accuracy tradeoffs for the three subject groups. If the CT manipulation is successful, RT should increase as a function of CT for all three groups. Mean RTs are plotted in Figure 8. It is readily apparent that RT does increase appropriately. An ANCOVA (Appendix 16) showed, once again, the significant effect of the covariate age, $F = 14.86$, $df = 1,40$, $p < .001$, together with significant main effects of CT, $F = 4.32$, $df = 2,82$, $p < .05$, and group, $F = 5.05$, $df = 2,40$, $p < .05$. No significant interactions were found.

Post hoc comparisons (Newman Keuls) revealed significant differences at the .05 level only between the severe and the control groups for the second and third criterion times.

Speed-Accuracy Trade-offs

Given that the CT manipulation successfully controls RT it is appropriate to plot speed-accuracy-trade-offs. Figure 9 shows such trade-offs where the measure of accuracy is d' chosen, as before, as the index of accuracy independent of any bias to choose the top or bottom line. Repeated measures ANCOVA (Appendix 17) with d' as the dependent measure revealed no significant main effects or interactions.

Figure 8: Mean RT as a Function of Group and
Criterion Time

Exp 3 - Overall Mean RT as a
Function of Group and Criterion Time

Figure 9: Mean d' Value as a Function of Group and CT

Mean d' as a Function
of Group and Criterion Time

Ratios and Differences of Line Length

The stimuli presented in Experiment III were pairs of horizontal lines. The actual difference between the lines was varied from presentation to presentation, as was the ratio of one line length to the other. Ratio and difference were manipulated independently, and stimulus lines were selected from a 5 x 5 (ratio x difference) matrix which described all possible non-redundant combinations of the five ratios and five differences studied were the same as in Experiment II.

Data were analysed using multivariate analyses of variance (MANOVA). The between-subjects factor was injury severity (3) and the within-subjects factors were line ratio (5), line difference (5), and criterion time (3).

Analyses revealed only a significant interaction between criterion time and line ratio, $F = 7.75$, $df = 4, 125$, $p < .001$, with Greenhouse-Geisser correction. All other interactions and all main effects failed to reach significance. A summary of MANOVA results is presented in Appendix 18. Mean correct RTs are plotted as a function of ratio and deadline in Figure 10.

DISCUSSION

The finding that severely head-injured patients had longer overall RTs than the control group is in keeping with the results of the previous two experiments. Because Experiments I, II and III were conducted in order for all Ss, the persistence of the significant slowing for the severe head injury group in this experiment strengthens the conclusions of the earlier

Figure 10: Mean Correct RT as a Function of Ratio and
Deadline (Criterion Time)

Exp 3 -
Mean Correct RT as a Function
of Ratio and Deadline (Criterion Time)

experiments and means that severely-injured patients did not simply take longer to "warm up" on the task.

However, it was also the case for all three groups that RT varied as a function of criterion time (CT). In other words, for all three groups the time taken to respond was a function of the time allowed for the response.

Accuracy, as measured by d' , did tend to vary with CT. However, severity of head injury did not significantly effect speed-accuracy tradeoffs. Mildly head-injured and even severely head-injured children appear capable of increasing the speed of their responses on this relatively complex task with only a minimal sacrifice of response accuracy. Once again, this finding supports the idea that severely head-injured children, while demonstrably slower, do not seem to process information in a fundamentally different fashion, or according to different criteria, than the mildly head-injured and control children. Future research should aim to strengthen this finding by the use of a wider range of CTs, including shorter CTs to determine the limits of rapid responding in the clinical group.

Analyses of the effects of ratio and differences of line length on RT did not present a coherent picture. Physical differences in line length did not have a significant effect on RT as they did in the previous experiment. Furthermore, a significant interaction between CT and ratio of line lengths was revealed. On the face of it, such an interaction would be plausible, suggesting that perhaps the additional stress of an imposed short CT might accentuate an otherwise small or

negligible effect of line ratios. However, as is clear from Figure 10, no coherent picture of the relationship between the ratio of stimulus lines and RT is discernible.

(VIII) GENERAL DISCUSSION

The frequency of head injury among children is increasing and head injury is a prominent factor in child mortality. All aspects of this phenomenon need attention, the most obvious being prevention, especially in the area of motor vehicle accidents where injuries tend to be severe and avoidable. The bulk of injuries sustained are closed head injuries, but depressed skull fractures and focal lesions resulting from blunt impact are not rare. Neurological advances have dramatically changed the prognostic picture faced by the victims of head injury and their parents. In particular, use of induced barbiturate coma and artificial respiration in conjunction with intracranial pressure monitoring in children has greatly reduced the occurrence of secondary brain damage in this population and has allowed the survival of countless children who, only several years ago, would have died from their injuries. The increasing frequency of head injury and increasing survival rates naturally raise questions in the medical and popular literatures concerning the quality of life of survivors. While the spontaneous recovery from head injury is often drastic, and rehabilitation programs (and journals such as Cognitive Rehabilitation) are becoming more popular, the extent of recovery after head injury, whether spontaneous or through rehabilitation, has, to date, been poorly quantified and understood.

Brain damage resulting from head injury is typically diffuse in nature, and as a result, research into the effects of closed head injury has not focused primarily on anatomical-psychological

relationships, but rather has emphasized the relation of psychological deficits to global indices of injury severity such as duration of coma or post-traumatic amnesia. Neuropsychologists have established several such relationships. It is known, for example, that children's I.Q. scores tend to be reduced after head injury by ten to thirty points and that although improvements in these scores over time are typical, deficits tend to persist, especially in young children and those with residual neuropsychological deficits. Motor and sensory/perceptual deficits have also frequently been reported, and the extent of these deficits, as well as intellectual deficits, has been positively related to the depth and duration of coma or PTA (see Winogron et al., 1984).

The current research was guided by ideas which grew out of recent findings by Chadwick and his co-workers (1981), which were subsequently confirmed by Winogron, Knights and Bawden (1984). Chadwick's group reported that the tests in a neuropsychological test battery most likely to be affected by head injury were those which relied heavily on rapid responses and assessed visuo-motor and visuo-spatial skills. Winogron et al. found that measures which showed differential deficits across head injury severity groups were all timed tests. Bawden, Knights and Winogron (1985) further showed that head-injured children who showed deficits on tests requiring motor speed and visual-spatial skills did not show generalized deficits of either motor or visuo-spatial abilities. Thus, speed of performance seemed to be the primarily affected dimension.

These findings began to impose some order on the seemingly random patterns of neuropsychological deficits observed in head-injured patients. However, clinical tests are not designed to, and in fact do not, measure a single aspect of psychological functioning. The element of speed "extracted" from several psychological tests merely suggested that speed of performance may account for the deficits on tests of diverse psychological functions. The reaction time research reported here was intended to investigate whether a slowing of information processing was, in fact, common among head injured patients, and also to investigate, in more detail, the nature of any observed slowing in responses.

Previous studies of RT in samples of head-injured adults, while not numerous, have produced a number of findings. Head-injured patients are known to be slower than non-injured adults on simple and choice RT tasks for prolonged periods after trauma, and differences between head-injured and normal control groups are known to generally grow larger as the complexity of RT tasks increases. Severely-injured patients have been shown to experience greater slowing than mildly- and moderately-injured patients, especially on choice RT tasks. However, on the topic of pediatric head injury, virtually nothing could be stated with confidence. The current research was designed to address several specific questions.

The first experiment in the present study examined the hypotheses that head-injured children would be slower on a simple RT task, that their performances would be more variable, and that

the distributions of their RTs would be more positively skewed than would those of matched normal controls. RT and response variability were expected to decrease with increasing FPs for the control group but less so, or not at all for the brain-damaged groups.

The first hypothesis was confirmed. The severely-injured patients were, on average, significantly slower than were the normal controls. While this result has not satisfactorily been demonstrated in previous research, a more interesting and perhaps more surprising finding was that the relation between FP and RT was the same for all three subject groups. For all groups, RT decreased for longer FPs up to 4 sec and then levelled off at 5 sec. These results indicate that head-injured children, even the severely-injured, are capable of processing probabilistic information - they were able to anticipate stimulus onsets based on the conditional probabilities of immediate onset. It has been demonstrated that head-injured patients, although slower than non-head-injured persons, are capable of doing this type of task, which despite its label as a 'simple' RT task, requires some reasonably complex data processing. The data from the first experiment also revealed that standard deviations considered to be indicative of 'preparedness to respond' decreased as a function of FP for all groups. This confirms the above conclusion. Furthermore, the finding of greater variability for the severely-injured children than the mildly-injured children suggests that injury severity did determine, to some degree, the extent to which children could employ this probabilistic

information to their advantage. The lack of significant interaction between FP and group in the analyses of standard deviation data again suggests that all the groups approached the task in a comparable fashion.

The hypothesis that positive skew would be greater for the head injury groups, reflecting a greater number of stifled anticipations, was not confirmed. The use of experimental instructions which implicitly discouraged anticipations likely accounts for this failure to find significance. Modification of these instructions, which were intended to simplify the task for younger children, perhaps with a sample of older children, may resolve this problem in future.

The finding that no simple relationship exists between post-traumatic I.Q. and RT has not previously been reported for a pediatric sample. This result is important because it offers reassurance that the slowing of visuo-motor performance is an independent entity and is not simply accounted for by lowered post-traumatic I.Q.

The issues of whether head injury patients would be significantly slower than controls on a choice RT task, and whether slowing, if observed, would be accompanied by a decrease in response accuracy were investigated in the second experiment. Also examined was the hypothesis that, for head-injured patients, RTs for correct responses would, on average, be shorter than error RTs, reflecting a conservative response bias (the favouring of accuracy over speed).

The results were informative and, once again, surprising in

some ways. Not unexpected was the finding that overall mean RT and the mean RT for correct responses were significantly longer for the severes than for the milds and controls. The task employed here did not merely require patients to push one of several buttons corresponding to the onset of one of several stimuli, rather, it necessitated the evaluation and comparison of simultaneously-presented stimuli. This complex task was sufficiently sensitive to discriminate between the mildly- and severely-injured groups, whereas the task used in Experiment I was not. The failure to find significant differences between RTs for correct and error responses negates the hypothesized difference in response strategies between head-injured and non-head-injured children. Head-injured patients do not appear to adopt particularly conservative response strategies. This conclusion is consistent with the fact that no significant group differences were found in the proportion of correct responses.

The final experiment addressed two particularly interesting questions around which much of this thesis was developed. The first question was whether imposing a ceiling or criterion time on RTs (and providing instant visual feedback to Ss concerning response speed and accuracy) would speed-up the responses of head-injured patients and if so, would the speeding-up be achieved at the expense of response accuracy. The data for overall mean RTs revealed significant effects for CT and for group, but no interaction between CT and group was found. Therefore controls and head-injured patients were affected similarly by the imposition of CTs - all groups had slightly

faster responses for the shorter CTs. While the severely-injured were generally slowed once again, all groups shortened their RTs to meet the imposed CTs. Once again, the difference between groups appears to be merely a difference of degree. The speed-accuracy tradeoffs in Figure 9 are an important demonstration that information processing is not qualitatively different in the three groups. Head-injured children, including the severely-injured, can perform a complex perceptual discrimination with a high degree of accuracy. Moreover, they can vary their speed of responding in a surprisingly flexible manner in accordance with task demands, with only a minimal decrease in response accuracy. At their fastest in Experiment III, i.e., when the CT was shortest, the severely-injured respond about as quickly as the control and mildly-injured groups in Experiment II.

This being so, it is reasonable to conclude that at least some of the slowing-down of responding observed in head-injured populations (see Winogron et al., 1985) is strategic in nature and does not purely reflect the inherent limitations of the system after injury. Response strategies may not of course be the sole determinants of slowness in the head injured but likely compound the existing problem.

The assumption that any behavioural deficits after head injury are purely determined by neurologic deficits (or "changes in the system") is often basic to discussion of head injury sequelae. The data of Experiment I would ordinarily be interpreted as showing the consequences of head injury in slowing

simple RT. However, as has already been observed "simple" RT is something of a misnomer. Theorists such as Ollman and Billington (1972) and Naatanen (1970) have demonstrated that there is ample scope for strategic behaviour even in such simple tasks. The detailed discussion earlier of the results of Experiment I, confirm this view. - All three subject groups responded strategically to probabilistic information. The ability of the head-injured groups to respond more rapidly to meet a deadline indicates that the generally slower responding of these subjects may represent a highly conservative response strategy. Head-injured subjects may require greater evidence of signal presentation before they are willing to respond.

As was discussed in section I-iv, the neuropathology resulting from closed head injury is quite predictable. The diffuse microscopic lesions resulting from shear strains at the time of impact are primarily concentrated in the frontal and temporal lobes (Grubb & Cox, 1978). The behavioural deficits ("frontal signs") resulting from such pathology have been described for adult samples. They include problems in regulating and controlling activity, and, conceptual and problem-solving behaviours (Hecaen & Albert, 1978; Lezak, 1979, Luria, 1966; Shacter & Crovitz, 1977). Others have described the behavioural effects, more generally, as a loss of mental speed or cognitive efficiency (e.g., Van Zomeren & Deelman, 1978).

Clearly, these behavioural manifestations of "frontal" damage in adult head injury victims parallel the types of behavioural signs shown by children in the current research. The implication

is that children also show signs of primarily frontal brain damage, and that the behavioural manifestations of closed head injury are similar for children and adults.

It is worth noting however, that some of the obvious symptoms of diffuse frontal damage, in particular what has been called "motor inertia", do not appear to be present in the groups of head-injured children studied here. Any simple theory of the commonly observed pattern of slowness in responding in head injured patients (see sections I and II) that attributes the slowness to mere motor slowness cannot account for the results of Experiment III. In passing, it may also be noted that theories which would attribute the slowness observed in Experiment I to simple sensory processing are also ruled out by the findings of Experiment III.

In practice, apart from the reasonable assumption that damage is likely to be primarily frontal and temporal in both the severe and mild groups, it is of dubious value to speculate further on the relations between the behavioural data reported for Experiments I, II and III, and the detailed anatomical considerations discussed in the introduction. Information in this latter regard is simply lacking for this sample.

Future research projects employing RT paradigms should attempt to test head-injured patients at various intervals post-trauma. While it is easy and typical for a researcher to endorse longitudinal research (as long as it is carried out by others), the issue of time since injury is particularly relevant for the study of severe head injury. The latency of

psychological evaluation in head injury studies has varied widely and methodological differences across studies generally prevent meaningful comparisons of findings. The inclusion of different severities of injury and different injury-test intervals within the same study is necessary. A better understanding of the natural time course of recovery will help determine the best times and approaches for rehabilitative intervention.

On a more technical level, researchers should be concerned with developing computer programs to control the CTs in choice RT studies in accordance with the abilities of the individual being tested. Patients should be pushed to respond as quickly as possible without sacrificing response accuracy. For example, CT on trial n of a choice RT task could be determined by the actual RT on trial $n-1$ if the response on $n-1$ was correct, or it could be controlled by the CT on trial $n-2$ (or $n-1$) if the response on trial $n-1$ was incorrect. What is being proposed is basically an automated "method of limits" type psychological procedure for establishing a threshold beyond which Ss cannot increase speed without sacrificing accuracy. The use of progressively more difficult discriminations with such an automated procedure would be useful in establishing learning curves for patients at different intervals post-trauma. Alternatively, such a procedure could be used periodically as a dependent measure to assess the efficiency of various visuo-spatial and motor rehabilitation programs, most of which are introduced to the market without evaluation.

The extension of RT tasks to vigilance-type tasks, with

hundreds of trials, would be useful in determining differences between normal controls and head-injured children in fatigueability and attention at various intervals post-trauma. Again, these data would help determine the course of future rehabilitation efforts.

Although the results do agree with those of other investigators who have found some slowing of responding in head-injured populations (e.g., Chadwick et al., 1981), detailed analyses of simple RT and comparison times show that head-injured and normal children process information in remarkably similar ways. That at least part of the slowness to respond after head injury reflects the head-injured child's flexible adjustment to situations is itself a significant cause for optimism in the rehabilitation of this population.

References

- Adams, J. H. (1975). The neuropathology of head injuries. In P. J. Vinken & G. W. Bruyn (eds.), Handbook of clinical neurology, vol. 23, New York: Elsevier.
- Adams, J. H., Mitchell, D. E., Graham, D. I., & Doyle, D. (1977). Diffuse brain damage of immediate impact type. Brain, 100: 489-502.
- Adams, J. H. & Graham, D. O. (1972). The pathology of blunt head injuries. In M. Critchley, J. O'Leary, & B. Jennett (eds.), Scientific foundations of neurology (pp. 489-491). London: Heinemann.
- Advani, S. H., Owings, R. P., & Schuck, L.Z. (1972). Response evaluation of translational and rotational head injury models. Shock and Vibration Digest, 4: 3-16.
- Annegers, J. F., Grabow, J. D., Kurland, L. T., & Laws, E. R. (1980). The incidence, causes and secular trends of head trauma in Olmsted County, Minnesota. Neurology, 30: 912-919.
- Baumeister, A., & Joubert, C. (19). Interactive effects on reaction time of preparatory interval length and preparatory interval frequency. Journal of Experimental Psychology, 82: 393-395.
- Bawden, H. M., Knights, R. M., & Winogron, H. W. (1985). Speeded performance following head injury in children. Journal of Clinical Neuropsychology, 7(1): 39-54.

- Becker, D. P., Miller, J. D., Ward, J. D., Greenberg, B. P.,
Young, H. F., & Sakalas, R. (1977). The outcome from severe
head injury with early diagnosis and intensive management.
Journal of Neurosurgery, 48: 491-502.
- Black, P., Jeffries, J. J., Blumer, D., Wellner, A., & Walker
A. E., (1969). The post-traumatic syndrome in children.
Characteristics and incidence. In A. E. Walker, W. F.
Caveness & M. Critchley (eds.), The late effects of head
injury. Springfield, Illinois: Charles C. Thomas.
- Blackburn, H. L. & Benton, A. L. (1955). Simple and choice
reaction time in cerebral disease. Confin. Neurol., 15,
327-338.
- Blishen, B. R. (1961). The construction and use of an
occupational class scale. In Canadian Society (pp.
477-485), Toronto: MacMillan.
- Boring, E. G. (1957). A history of experimental psychology (2nd
ed.). New York: Appleton-Century-Crofts.
- Brink, J. D., Garrett, A. L., Hale, W. R., Woo-Sam, J., &
Nickel, V. L. (1970). Recovery of motor and intellectual
function in children sustaining severe head injuries.
Developmental Medicine and Child Neurology, 12: 565-571.
- Bruce, D. A., Schut, L., Bruno, L. A., Wood, J. H., & Sutton
L. N. (1978). Outcome following severe head injury in
children. Journal of Neurosurgery, 48: 679:688.
- Bruhn, P., & Parsons, O. A. (1971). Continuous reaction time
in brain damage. Cortex, 7: 278-291.

- Buschke, H., & Fuld, P. A. (1974). Evaluating storage, retention and retrieval in disordered memory and learning. Neurology, 24: 1019-1025.
- Carlsson, C. A., Von Essen, C., & Lofgren, J. (1968). Factors affecting the clinical course of patients with severe head injuries. Part 1: Influence of biological factors. Part 2: Significance of Posttraumatic coma. Journal of Neurosurgery, 29: 242-251.
- Chadwick, O., Rutter, M., Brown, G., Shaffer, D. & Traub, M. (1981). A prospective study of children with head injuries. II: Cognitive sequelae. Psychological Medicine, 11:49-61.
- Chadwick, O., Rutter, M., Shaffer, D., & Shrout, P. E. (1981). A prospective study of children with head injuries. IV: Specific cognitive deficits. Journal of Clinical Neuropsychology, 3: 101-120.
- Courville, C. B. (1945). Effects of closed cranial injuries on the midbrain and upper pons. In Trauma of the Central Nervous System (pp. 131-150). Baltimore: Williams & Wilkins.
- Craft, A. W. (1972). Head injury in children. P.J. Vinken & G. W. Bruyn (eds.), Handbook of Clinical Neurology (pp. 445-458). Vol. 23, New York: Elsevier.
- Dencker, S. J., & Lofving, B. (1958). A psychometric study of identical twins discordant for closed head injury. Acta Psychiatrica Neurologica Scandinavica (Suppl.), 122: 119-126.
- Dunn, L. M., & Dunn, Leota M. (1981). Peabody picture vocabulary test-revised: Manual. Minnesota, AGS.

Field, J. H. (1976). Epidemiology of head injury in England and Wales: with particular application to rehabilitation.

Leicester: Printed for H. M. Stationery Office by William

Flach, J., & Malmros, R. (1972). A long-term follow-up study of children with severe head injury. Scandinavian Journal of Rehabilitation Medicine, 4: 9-15.

Freytag, E. (1963a). Autopsy findings in head injuries from blunt forces. Archives of Pathology, 75: 403-413.

Freytag, E. (1963b). Autopsy findings in head injuries from firearms. Archives of Pathology, 76: 215-225.

Fuld, P. A., & Fisher, P. (1977). Recovery of intellectual ability after closed head-injury. Developmental Medicine and Child Neurology, 19: 495-502.

Gaidolfi, E., & Vignolo, L. A. (1980). Closed head injuries of school-age children: Neuropsychological sequelae in early adulthood. Italian Journal of Neurological Science, 1: 65-73.

Gottadanker, R., & Way, T.C. (1966). Varied and constant intersignal intervals in psychological refractoriness. Journal of Experimental Psychology, 72: 792-804.

Granjon, M., & Reynard, G. (1977). Effect of the length of the runs of repetitions on the simple RT-ISI relationship. Quarterly Journal of Experimental Psychology, 29: 283-295.

Gronwall, D., & Sampson, H. (1974). The Psychological Effects of Concussion. Auckland: Auckland University Press.

- Grubb, R. L., & Cox, J. S. (1978). Trauma to the central nervous system. In S. G. Eliasson, A. L. Pinsky, & W. B. Hardin Jr. (Eds.), Neurological pathophysiology. New York: Oxford University Press.
- Gurdjian, E. S. (1971). Mechanisms of impact injury of the head. In Head Injuries (pp. 17-22). Proceedings of an International Symposium held in Edinburgh and Madrid. Edinburgh: Churchill Livingstone.
- Gurdjian, E. S. & Gurdjian, Edwin S. (1976). Cerebral contusions: Re-evaluation of the mechanism of their development. Journal of Trauma, 16: 35-51.
- Hecaen, H. & Albert, M. L. (1978). Human neuropsychology. New York.
- Hendrick, E. B., Hardwood-Hash, D. C. F., & Hudson, A. R. (1964). Head injuries in children: A survey of 4465 consecutive cases at the Hospital for Sick Children, Toronto, Canada. Clinical Neurosurgery, 11: 46-59.
- Holbourn, A. H. S. (1943). Mechanics of head injuries. Lancet, 2: 438-441.
- Ivan, L. P., Choo, S. H., & Ventureyra, E. C. G. (1980). Intracranial pressure monitoring with the fiberoptic transducer in children. Child's Brain, 7: 303-313.
- Jamieson, K. G., & Yelland, J. D. N. (1968). Extradural haematoma: Report of 167 cases. Journal of Neurosurgery, 29: 13-23.
- Jamison, D. L., & Kaye, H. H. (1974). Accidental head injury in children. Archives of Diseases in Childhood, 49: 376-381.

- Jellinger, K., & Seitelberger, F. (1970). Protracted post-traumatic encephalopathy: Pathology, pathogenesis and clinical implications. Journal of Neurological Science, 51-94.
- Jennett, B. (1972). Head injuries in children. Developmental Medicine and Child Neurology, 14: 137-147.
- Jennett, B. (1976). Assessment of the severity of head injury. Journal of Neurology, Neurosurgery and Psychiatry, 39: 647-655.
- Jennett, B., Teasdale, G., Galbraith, S., Pickard, J., Grant, H., Braakman, R., Avexaat, C., Maas, A., Minderhoud, J., Vecht, C. J., Heiden, J., Small, R., Caton, W., & Kurze, T. (1977). Severe head injuries in three countries. Journal of Neurology, Neurosurgery and Psychiatry, 40: 291-298.
- Johnston, R. B., & Mellits, E. D. (1980). Pediatric coma: Prognosis and outcome. Developmental Medicine and Child Neurology, 22: 3-12.
- Jones, B., & Duffy, J. (1982). An analysis of performance by pre-school children on the KRISP and on a length discrimination task. Acta Psychologica, 52: 197-211.
- Klatzo, I. (1967). Neuropathological aspects of brain damage. Journal of Neuropathology in Experimental Neurology, 26: 1-14.
- Klenner, E. T. (1956). Time uncertainty in simple reaction time. Journal of Experimental Psychology, 51: 179-184.
- Klenner, E. T. (1957). Simple reaction time as a function of time uncertainty. Journal of Experimental Psychology, 54: 195-200.

- Klensch, H. (1973). Die diagnostische Valenz der Reaktionszeitmessung bei Verschiedenen Zerebralen Erkrankungen. Cited in Van Zomeren, 1981.
- Klonoff, H. (1971). Head injuries in children: Predisposing factors, accident conditions, accident proneness and sequelae. American Journal of Public Health, 61: 2405-2417.
- Klonoff, H., & Paris, R. (1974). Immediate, short-term and residual effects of acute head injuries in children: neuropsychological and neurological correlates. In R. M. Reitan & L. A. Davison (eds.), Clinical neuropsychology: Current status and applications (pp. 179-210). New York: John Wiley & Sons.
- Klonoff, H., Robinson, G. C., & Thompson, G. (1969). Acute and brain syndromes in children. Developmental Medicine and Child Neurology, 11: 198-213.
- Klonoff, H., Low, M. D., & Clark, C. (1977). Head injuries in children: A prospective five year follow-up. Journal of Neurology, Neurosurgery and Psychiatry, 40: 1211-1219.
- Knights, R. M., & Ivan, L. P. (1984). Handicaps as a Consequence of Head Injury in Children. Final report to Ontario Ministry of Health, June.
- Knights, R. M., & Moule, A. (1967). Normative and reliability data on finger and foot tapping in children. Perceptual and Motor Skills, 25: 717-720.
- Knights, R. M., & Norwood, J. A. (1979). A neuropsychological test battery for children: Examiner's manual. Psychological Consultants, Ottawa.

- Kobrine, A. I., Timmins, E., Rajjoub, R. K., Rizzoli, H. V., & Davis, D. O. (1977). Demonstration of massive traumatic brain swelling within 20 minutes after injury. Case Report. Journal of Neurosurgery, 46: 256-258.
- Kohfeld, D. (1969). Effects of the intensity of auditory and visual ready signals on simple reaction time. Journal of Experimental Psychology, 82: 88-95.
- Kornblum, S. (1973). Simple reaction time as a race between signal detection and time estimation: A paradigm and model. Perception and Psychophysics, 13: 108-112.
- Langfitt, T. W., Tannenbaum, H. M., & Kassell, N. F. (1968). The etiology of acute brain swelling following experimental head injury. Journal of Neurosurgery, 24: 47-56.
- Levin, H. S., Benton, A. L. & Grossman, R. G. (1982). Neurobehavioral consequences of closed head injury. New York: Oxford University Press.
- Levin, H. S., & Eisenberg, H. M. (1979a). Neuropsychological outcome of closed head injury in children and adolescents. Child's Brain, 5: 281-292.
- Levin, H. S., & Eisenberg, H. M. (1979b). Neuropsychological impairment after closed head injury in children and adolescents. Journal of Pediatric Psychology, 4: 389-401.
- Lezak, M. D. (1979). Recovery of memory and learning functions following traumatic brain injury. Cortex, 15, 63-70.
- Lindenberg, R. (1971). Trauma of meninges and brain. In J. Minchler (ed.), Pathology of the nervous system, Vol. 2 (pp. 1705-1765). New York: McGraw Hill.

- Link, S. W. (1971). Applying RT deadlines to discrimination reaction time. Psychonomic Science, 25: 355-358.
- Link, S. W., & A. D. Tindall (1971). Speed and accuracy in comparative judgements of line length. Perception & Psychophysics, 9: 284-288.
- Luria, A. R. (1966). Higher cortical functions in man (B. Haigh, trans.). New York: Basic Books.
- Maloney, A. F. J., & Whatmore, W. J. (1969). Clinical and pathological observations in fatal head injuries: a 5-year survey of 173 cases. British Journal of Surgery, 56: 23-31.
- McCormack, P. D., & N. M. Wright (1964). The positive skew observed in reaction time distributions. Canadian Journal of Psychology, 18: 43-51.
- Miller, E. (1970). Simple and choice reaction time following severe head injury. Cortex, 6: 121-127.
- Miller, H. (1961). Accident neurosis. British Medical Journal, 1: 919-925, 992-998.
- Miller, J. D., Butterworth, J. F., Gudeman, S. K., Faulkner, J. E., Choi, S. C., Selhorts, J. B., Harbison, J. W., Lutz, H. A., Young, H. F., & Becker, D. P. (1981). Further experience in the management of severe head injury. Journal of Neurosurgery, 54: 289-299.
- Naatanen, R. (1970). The diminishing time-uncertainty with the lapse of time after the warning signal in reaction-time experiments with varying fore-periods. Acta Psychologica, 34: 399-419.

- Naatanen, R., & Merisaalo, A. (1977). Expectancy and preparation in simple reaction time. In S. Dornic (Ed.), Attention and Performance VI. Hillsdale, N.J.: Erlbaum.
- Newcombe, F. (1969). Missile wounds of the brain: A study of psychological deficits. New York: Oxford University Press.
- Niemi, P. (1979). Stimulus intensity effects on auditory and visual reaction processes. Acta Psychologica, 43: 299.
- Niemi, P., & Naatanen, R. (1981). Foreperiod and simple reaction time. Psychological Bulletin, 89: 133-161.
- Norman, B., & Svahn, K. (1961). A follow-up study of severe brain injuries. Acta Psychiatrica Scandinavica, 37: 236-264.
- Ollman, R., & Billington, M. (1972). The deadline model for simple reaction times. Cognitive Psychology, 3: 311-336.
- Ommaya, A. K., & Gennarelli, T. A. (1974). Cerebral concussion and traumatic unconsciousness: Correlation of experimental and clinical observations on blunt head injuries. Brain, 97: 633-643.
- Ommaya, A. K., Grubb, R. L., & Naumann, R. A. (1971). Coup and contre-coup: Observations on the mechanics of visible brain injuries in the rhesus monkey. Journal of Neurosurgery, 35: 503-517.
- Pachella, R. G. (1974). The interpretation of reaction time in information processing research. In B. Kantowitz (ed.), Human information processing: Tutorials in performance and cognition. Potomac, MD: Erlbaum.

- Pachella, R. G., & Fisher, D. F. (1972). Hick's law and the speed-accuracy trade-off in absolute judgment. Journal of Experimental Psychology, 92: 378-384.
- Petrusic, W. M., & Jamieson, D. G. (1979). Resolution time and the coding of arithmetic relations on supraliminally different visual extents. Journal of Mathematical Psychology, 19: 89-107.
- Possamai, C.-A., Granger, M., Requin, J., & Reynard, G. (1973). Sequential effects related to foreperiod duration in simple reaction time. Perceptual and Motor Skills, 36: 1185-1186.
- Pudenz, R. H., & Shelden, C. H. (1946). The lucite calvarium - a method for direct observation of the brain: II. Cranial trauma and brain movement. Journal of Neurosurgery, 3: 487-505.
- Reitan, R. M., & Davison, L. A. (1974). Clinical neuropsychology: Current status and applications. New York: Hemisphere.
- Reusch, J. (1944). Dark adaptation, negative after images, tachistoscopic examination and reaction time in head injuries. Journal of Neurosurgery, 1: 243-251.
- Richardson, F. (1963). Some effects of severe head injury. A follow-up study of children and adolescents after protracted coma. Developmental Medicine and Child Neurology, 5: 471-482.
- Sanders, A. (1966). Expectancy: Application and measurement. Acta Psychologica, 25: 293-313.

- Schacter, D. L., & Crovitz, H. F. (1977). Memory function after closed head injury. A review of the quantitative research. Cortex, 13, 150-176.
- Stover, S. L., & Zeiger, H. E. Jr. (1976). Head injury in children and teenagers: Functional recovery correlated with the duration of coma. Archives of Physical Medicine and Rehabilitation, 57: 201-205.
- Strich, S. J. (1956). Diffuse degeneration of the cerebral white matter in severe dementia following head injury. Journal of Neurology, Neurosurgery and Psychiatry, 19: 163-185.
- Strich, S. J. (1961). Shearing of nerve fibres as a cause of brain damage due to head injury. Lancet, 11: 443-448.
- Strich, S. J. (1969). The pathology of brain damage due to blunt head injuries. In A. E. Walker, W. F. Caveness, & M. Critchley (eds.), The late effects of head injury (pp. 501-526). Springfield: Charles C. Thomas.
- Strich, S. J. (1970). Lesions in the cerebral hemispheres after blunt head injury. In S. Sevitt & H. B. Stoner (eds.), The pathology of trauma (pp. 166-171). London: BMA House.
- Surwillo, W. W. (1971). Human reaction time and period of the electroencephalogram in relation to development. Psychobiology, 8: 468-482.
- Surwillo, W. W., & Titus, T. (1976). Reaction time and the psychological refractory period in children and adults. Developmental Psychobiology, 9(6): 517-527.

- Swenson, R. G. (1972). The elusive tradeoff: Speed versus accuracy in visual discrimination tasks. Perception and Psychophysics, 12: 16-32.
- Swenson, R. G. (1973). The elusive tradeoff: Speed vs. accuracy in visual discrimination tasks. Perception and Psychophysics, 12, 16-32.
- Teasdale, G., & Jennett, B. (1974). Assessment of coma and impaired consciousness. A practical scale. Lancet, 2: 81-84.
- Teasdale, G. M., Knill-Jones, R., & Jennett, B. (1974). Assessing and recording conscious level. Journal of Neurology, Neurosurgery and Psychiatry, 37: 1286.
- Troupp, H. (1967). Intraventricular pressure in patients with severe brain injuries. Journal of Trauma, 7: 876-883.
- Van Zomeren, A. H. (1981). Reaction time and attention after closed head injury. Lisse: Swets and Zeitlinger.
- Van Zomeren, A. H., & Deelman, B. G. (1978). Differential effects of simple and choice reaction after closed head injury. Clinical Neurology and Neurosurgery, 79: 81-90.
- Van Zomeren, A. H., & Deelman, B. G. (1978). Long-term recovery of visual reaction time after closed head injury. Journal of Neurology, Neurosurgery and Psychiatry, 41: 452-456.
- Vapalahti, M., & Troupp, H. (1971). Prognosis for patients with severe brain injuries. British Medical Journal, 3: 404-407.
- Vickers, D. (1979). Decision processes in visual perception. New York: Academic Press.

Winogron, H. W., Knights, R. M., & Bawden, H. M. (1984).

Neuropsychological deficits following head injury in children. Journal of Clinical Neuropsychology, 6: 269-286.

Wood, C. C., & Jennings, R. (1976). Speed-accuracy tradeoff: functions in choice reaction time: Experimental design and computational procedures. Perception and Psychophysics, 14: 92-101.

Woo-Sam, J., Zimmerman, I. L., Brink, J. D., Uyehara, K., & Miller, A. (1970). Socio-economic status and post-traumatic intelligence in children with severe head injuries. Psychological Report, 27: 147-153.

Zahn, T. P., Rosenthal, D., & Shakow, D. (1963). Effects of irregular preparatory intervals on reaction time in schizophrenia. Journal of Abnormal and Social Psychology, 67: 44-52.

Appendix One
Glasgow Coma Scale (GCS)

Eye Opening (E)

spontaneous	4
to sound	3
to pain	2
never	1

Best Motor Response (M)

obeys commands	6
localizes	5
flexion; normal	4
flexion; abnormal	3
extension	2
nil	1

Best Verbal Response (V)

oriented	5
confused	4
inappropriate	3
incomprehensible	2
none	1

EMV score = 3 - 15

Appendix Two

Exp. 1: Repeated Measures Analysis of Covariance for Mean
Correct RT; Covariate Age

Source	df	MS	F	P
A: Group	2	116997.1	3.77	.03
B: Age	1	386945.7	12.46	.001
error	39	31065.7		
C: FP	4	194912.3	44.00	.0000
AXC	8	5712.4	1.29	.25
error	160	4430.1		

Appendix Three

Repeated Measures Analysis of Covariance for Mean Correct RT;
Covariate Injury-Test Interval (ITI)

Source	df	MS	F	P
A: Group	1	60795.5	1.42	.24
B: ITI	1	1106.2	.03	.87
error	25	42709.6		
C: FP	4	148055.7	33.87	.0000
AXC	4	7271.9	1.66	.16
error	104	4371.3		

Appendix Four

Exp. 1: Repeated Measures Analysis of Covariance for
Median Correct RT; Covariate Age

Source	df	MS	F	P
A: Group	2	161707.	4.89	.01
B: Age	1	749255.1	22.22	.0000
error	39	53714.8		
C: FP	4	96786.7	47.39	.0000
AXC	8	1052.1	0.61	.77
error	160	2042.5		

Appendix Five

Repeated Measures Analysis of Covariance for Median
Correct RT; Covariate ITI

Source	df	MS	F	P
A: Group	1	77776.2	1.35	.26
B: ITI	1	14969.2	0.26	.62
error	25	57763.5		
C: FP	4	75933.9	34.45	.0000
AXC	4	892.8	0.42	.80
error	104	2146.3		

Appendix Six

Exp. 1: Repeated Measures Analysis of Covariance for
Standard Deviations; Covariate Age

Source	df	MS	F	P
A: Group	2	77391.8	3.83	.03
B: Age	1	199801.7	9.89	.003
error	39	20212.5		
C: FP	4	66173.2	8.57	.0000
AXC	8	10958.3	1.42	.19
error	160	7718.2		

Appendix Seven

Exp. 1: Repeated Measures Analysis of Covariance for
Standard Deviations; Covariate ITI

Source	df	MS	F	P
A: Group	1	125732.8	4.85	.04
B: ITI	1	12119.4	0.47	.50
error	25	25950.2		
C: FP	4	69301.9	8.18	.00000
AXC	4	4422.8	0.52	.72
error	104	8471.1		

Appendix Eight

Exp. 1: Repeated Measures Analysis of Covariance

for Skew; Covariate Age

Source	df	MS	F	P
A: Group	2	0.5076	0.39	.68
B: Age	1	0.4724	0.32	.58
error	39	1.4977		
C: FP	4	0.4057	0.58	.68
AXC	8	0.8020	1.14	.34
error	160	0.7019		

Appendix Nine

Repeated Measures Analysis of Covariance

for Skew; Covariate ITI

Source	df	MS	F	P
A: Group	1	0.40521	0.33	.57
B: ITI	1	0.13259	0.11	.75
error	25	1.22088		
C: FP	4	0.69985	1.00	.41
AXC	4	0.92365	1.38	.25
error	104	0.66875		

Appendix T

Exp. 2: Analysis of Covariance for Overall Mean RT;

Covariate Age

Source	df	MS	F	P
A: Group	2	307983.8	5.79	.006
B: Age	1	1113161.4	20.92	.0000
error	40	53219.9		

Appendix Eleven

Exp. 2: Analysis of Covariance for Mean Correct RT;

Covariate Age

Source	df	MS	F	P
A: Group	2	316653.5	5.92	.006
B: Age	1	1102118.5	20.59	.0001
error	40	53525.3		

Appendix Twelve

Exp. 2: Analysis of Covariance for Mean Error RT;

Covariate Age

Source	df	MS	F	P
A: Group	2	459349.4	02.16	.1314
B: Age	1	1902027.1	08.94	.0052
error	33	212683.1		

Appendix Thirteen

Exp. 2: Repeated Measures Analysis of Covariance for
Correctness; Covariate Age

Source	df	MS	F	P
A: Group	2	876161.4	4.14	.03
B: Age	1	2731798.5	12.91	.001
error	33	211669.5		
C: Correctness	1	20627.4	0.37	.55
AXC	2	1575.8	0.03	.97
error	34	56277.9		

Appendix Fourteen

Exp. 2: Analysis of Covariance for d' Values;
Covariate Age

Source	df	MS	F	P
A: Group	2	.086	0.25	.78
B: Age	1	.453	1.35	.26
error	31	.336		

Appendix Fifteen

MANOVA Summary Table - Experiment II

Source	df	MS	F	P
A: Group	2	7084370.0	3.72	.043
error	41	1905029.1		
B: Ratio	3	97348.5	1.54	.209
A x B	6	38553.3	0.61	.720
error	120	63364.5		
C: Difference	3	327318.0	4.57	.064
A x C	6	123620.0	1.73	.114
error	133	71555.6		
D: B x C	5	132525.0	2.48	.082
A x B x C	10	54366.9	1.02	.432
error	211	53519.5		

*Greenhouse-Geisser adjustment for degrees of freedom.

Appendix Sixteen

Exp. 3: Repeated Measures Analysis of Covariance for
Overall Mean RT; Covariate Age

Source	df	MS	F	P
A: Group	2	241882.9	5.05	.01
B: Age	1	712083.5	14.86	.0004
error	40	47912.6		
C: CT	2	23748.7	4.32	.02
AXC	4	2299.6	0.42	.80
error	82	5503.5		

Appendix Seventeen

Exp. 5: Repeated Measures Analysis of Covariance for d';
Covariate Age

Source	df	MS	F	P
A: Group	2	.653	0.41	.67
B: Age	1	.832	0.52	.47
error	40	1.590		
C: CT	2	.211	1.92	.15
AXC	4	.050	0.45	.77
error	82	.111		

Appendix Eighteen
MANOVA Summary Table - Experiment III

Source	df	MS	F	P
A: Group	2	4456650.	2.39	.110
error	29	1865180.5		
B: CT	2	9798.4	0.72	.463
A x B	3	10094.8	0.54	.539
error	47	13523.6		
C: Ratio	2	82592.0	1.75	.178
A x C	5	45177.7	0.96	.446
error	67	47281.4		
Difference				
(D)	3	54475.7	1.62	.194
A x D	6	20668.9	.61	.706
error	81	33607.9		
B x C	4	223537.0	7.75	.000
A x B x C	9	24534.7	0.85	.567
error	125	28834.2		
B x D	3	48824.6	1.56	.199
A x B x D	7	26279.8	0.84	.555
error	99	31304.6		
C x D	5	36721.7	1.32	.258
A x C x D	10	31695.6	1.14	.338
error	151	27886.5		
B x C x D	5	54183.0	1.45	.209
AxBxCxD	10	30648.6	0.82	.609
error	145	37316.3		

*Greenhouse-Geisser adjustment for degrees of freedom.

Appendix 19

Data Used in Analyses:

Contents

- Nineteen a - Exp. 1; Average RTs (and standard deviations) for each FP
- Nineteen b - Exp. 1; Average Median RTs (and standard deviations) for each FP
- Nineteen c - Exp. 1; Average Intra-subject Variability (and standard deviations) for each FP
- Nineteen d - Exp. 1; Average Skew (and standard deviations) for each FP
- Nineteen e - Exp. 2; Overall Mean RTs (and standard deviations) for severely- and mildly-injured children and controls
- Nineteen f - Exp. 2; Mean RTs (and standard deviations) as a Function of Group and Line Ratio, and Line Difference
- Nineteen g - Exp. 3; Mean RT Correct and Mean RT error (and standard deviations) for Severe, Mild and Control Groups at each Criterion Time
- Nineteen h - Exp. 3; Mean d' Values (and standard deviations) for Severe, Mild and Control Groups at each Criterion time
- Nineteen i - Exp. 3; Mean RTs (and standard deviations) for Severely- and Mildly-Injured and Control Children as a function of Stimulus Ratio, Stimulus Difference, and Criterion Time

Appendix Nineteen: a

FP	Severe	Mild	Control
1	650.8 (179.0)*	557.4 (121.5)	512.4 (164.3)
2	505.3 (122.8)	493.6 (110.2)	458.0 (115.8)
3	476.0 (85.7)	426.3 (79.1)	394.7 (80.4)
4	433.6 (71.3)	398.9 (65.2)	374.6 (65.6)
5	465.1 (104.7)	445.1 (96.3)	391.8 (69.4)

Appendix Nineteen: b

FP	Severe	Mild	Control
1	594.6 (126.7)*	554.0 (105.9)	487.1 (137.2)
2	537.0 (113.1)	491.8 (120.4)	440.7 (97.2)
3	500.6 (144.1)	445.1 (87.1)	416.1 (93.2)
4	478.4 (127.7)	415.4 (77.4)	390.5 (85.0)
5	479.4 (111.1)	444.4 (108.8)	393.7 (80.1)

Appendix Nineteen: c

FP	Severe	Mild	Control
1	287.9 (207.8)*	197.8 (96.5)	169.5 (132.8)
2	150.6 (80.4)	111.6 (65.8)	163.3 (108.7)
3	186.3 (114.3)	102.1 (59.5)	111.3 (44.3)
4	142.0 (90.3)	90.0 (51.8)	126.3 (88.9)
5	167.9 (148.0)	131.2 (77.3)	106.1 (96.7)

Appendix Nineteen: d

FP	Severe	Mild	Control
1	1.27 (.80)*	1.45 (1.03)	1.43 (.76)
2	1.28 (.74)	.89 (.63)	1.28 (.83)
3	1.42 (.89)	.85 (.96)	1.23 (.99)
4	1.08 (.80)	1.04 (.57)	1.56 (1.25)
5	1.25 (.99)	1.52 (1.18)	1.15 (1.11)

Appendix Nineteen: e

	Severe	Mild	Control
Mean (S.D.)	1090.3 (309.0)*	916.6 (276.1)	817.7 (255.6)

*Bracketed values are standard deviations.

Appendix 19: f

Group

Line	Line	Severe	Mild	Control
Ratio	Difference			
1	1	1173 (573.6)	996.5 (462.9)	903.3 (441.5)
1	2	1218 (556.2)	834.0 (232.3)	745.7 (201.2)
1	3	1041 (277.2)	955.0 (394.5)	838.5 (259.6)
1	4	1062 (370.1)	916.2 (304.0)	752.7 (222.3)
1	5	1045 (354.4)	901.6 (278.9)	840.1 (326.6)
2	1	1102 (603.0)	826.6 (185.7)	758.5 (248.9)
2	2	1097 (398.5)	921.1 (377.6)	914.7 (349.1)
2	3	992.3 (274.2)	1014.0 (434.0)	862.0 (303.1)
2	4	1195 (396.7)	888.1 (217.9)	896.2 (376.8)
2	5	1073 (287.4)	1045.0 (388.9)	844.5 (249.7)
3	1	1080 (480.4)	814.9 (191.0)	723.7 (210.9)
3	2	999.4 (293.7)	828.1 (164.6)	779.9 (287.1)
3	3	1054 (283.6)	907.8 (346.1)	782.1 (238.0)
3	4	1119 (421.2)	912.0 (324.4)	746.7 (230.5)
3	5	1027 (360.6)	969.7 (318.2)	870.2 (288.4)
4	1	1119 (518.8)	850.9 (203.4)	871.3 (370.5)
4	2	1062 (367.8)	845.9 (257.0)	801.2 (392.5)
4	3	943.2 (335.7)	834.9 (309.2)	813.7 (268.8)
4	4	1204 (956.4)	867.9 (240.3)	814.6 (248.4)
4	5	1345 (619.2)	1071.0 (404.0)	875.9 (275.1)
5	1	8977 (227.4)	849.9 (187.9)	785.1 (264.2)
5	2	1154 (585.8)	884.5 (272.2)	764.2 (263.6)
5	3	965.3 (346.2)	978.2 (357.4)	772.3 (224.7)
5	4	1122 (276.7)	970.9 (411.1)	801.9 (185.1)
5	5	1208 (447.4)	1033.0 (346.0)	960.3 (410.0)

Appendix Nineteen: g

		Severe	Mild	Control
RTc	CT1**	809.0 (145.0)**	710.6 (125.3)	656.6 (99.7)
	CT2	844.2 (170.2)	773.9 (166.2)	686.7 (154.0)
	CT3	867.7 (195.1)	773.1 (182.1)	724.7 (167.3)
RTe	CT1	979.2 (671.0)	646.7 (130.7)	723.6 (292.5)
	CT2	824.6 (252.1)	760.2 (181.5)	662.2 (165.9)
	CT3	840.0 (261.2)	645.0 (165.9)	744.1 (307.1)

**CT1 = 2000 ms, CT2 = 1500 ms, CT3 = 1000 ms

Appendix Nineteen: h

CT		Severe	Mild	Control
2000	d'	2.30 (1.12)*	2.51 (0.56)	2.62 (0.55)
1500	d'	2.29 (1.00)	2.50 (0.62)	2.41 (0.51)
1000	d'	2.22 (0.97)	2.41 (0.75)	2.39 (0.55)

*Bracketed values are standard deviations

Appendix Nineteen: 1

Criterion Time = 1000 msec

Line Ratio	Line Difference	Severe	Mild	Control
1	1	773.2 (118.8)	791.0 (258.0)	703.1 (310.9)
	2	764.3 (149.8)	828.3 (209.3)	703.2 (164.6)
	3	846.0 (245.3)	766.5 (156.0)	661.0 (84.3)
	4	812.6 (192.8)	756.2 (148.8)	606.1 (121.4)
	5	838.6 (280.2)	769.6 (190.6)	670.5 (192.5)
2	1	857.9 (447.6)	789.1 (205.4)	668.9 (173.8)
	2	775.6 (130.6)	739.2 (109.7)	691.6 (151.5)
	3	922.0 (381.0)	747.2 (169.7)	646.0 (150.4)
	4	833.1 (214.8)	726.3 (147.2)	715.7 (179.8)
	5	823.9 (343.2)	716.1 (135.7)	609.2 (115.7)
3	1	1021.0 (546.2)	833.7 (244.1)	729.8 (233.8)
	2	869.8 (396.0)	864.6 (369.0)	733.8 (191.0)
	3	862.7 (227.8)	706.4 (150.6)	645.1 (159.3)
	4	762.8 (199.9)	743.6 (155.3)	614.7 (124.2)
	5	861.7 (356.6)	737.8 (256.3)	700.4 (233.2)
4	1	725.4 (151.2)	694.2 (135.0)	606.4 (160.5)
	2	754.0 (135.9)	716.2 (172.6)	588.8 (151.6)
	3	818.9 (235.3)	739.8 (189.1)	661.6 (192.3)
	4	775.8 (239.9)	728.5 (143.6)	654.3 (131.7)
	5	755.7 (173.7)	817.2 (310.7)	635.5 (168.8)
5	1	788.1 (134.6)	905.8 (300.7)	683.7 (175.7)
	2	700.2 (161.6)	622.8 (105.3)	650.2 (152.0)
	3	751.1 (244.1)	774.0 (301.7)	593.8 (102.0)
	4	806.0 (255.5)	705.2 (158.9)	632.1 (107.1)
	5	736.0 (148.4)	757.2 (234.6)	622.4 (115.6)

Criterion Time = 1500 msec

1	1	752.1 (183.5)	823.7 (266.3)	640.2 (116.3)
	2	816.6 (242.3)	738.0 (177.0)	664.5 (181.0)
	3	976.4 (437.2)	848.3 (287.3)	623.1 (143.7)
	4	988.4 (472.1)	793.9 (154.2)	790.3 (542.4)
	5	889.0 (521.5)	760.8 (163.5)	829.4 (468.9)
2	1	837.7 (323.1)	691.5 (154.2)	669.7 (160.0)
	2	753.0 (215.5)	673.8 (148.4)	611.1 (137.0)
	3	764.1 (211.2)	818.4 (295.7)	635.5 (117.2)
	4	747.9 (253.9)	679.0 (133.5)	680.1 (185.3)
	5	704.9 (161.5)	688.6 (145.8)	594.2 (117.0)
3	1	740.3 (135.1)	660.9 (163.7)	715.8 (216.1)
	2	793.0 (206.7)	781.7 (185.4)	644.0 (136.1)
	3	712.8 (155.6)	779.6 (281.3)	598.4 (140.1)
	4	795.1 (253.8)	809.5 (339.1)	644.3 (122.0)
	5	819.8 (229.5)	695.0 (146.5)	660.6 (271.0)
4	1	774.1 (216.9)	756.2 (198.3)	638.6 (150.7)
	2	792.0 (258.7)	722.5 (129.6)	591.8 (115.5)
	3	802.4 (161.5)	774.8 (142.7)	585.3 (73.0)
	4	775.8 (227.7)	716.0 (141.3)	625.8 (182.7)
	5	795.2 (155.0)	1101.0 (1061.0)	684.6 (137.3)
5	1	778.9 (282.2)	743.0 (204.7)	601.5 (107.0)
	2	793.1 (149.3)	754.9 (183.5)	692.5 (153.8)
	3	750.8 (117.9)	722.5 (184.6)	596.5 (123.2)
	4	744.8 (125.8)	763.6 (170.1)	611.5 (117.4)
	5	812.3 (289.0)	749.0 (189.3)	683.2 (192.1)

Criterion Time = 2000 msec

Line Ratio	Line Difference	Severe	Mild	Control
1	1	849.4 (250.5)	798.4 (272.5)	654.1 (167.2)
	2	863.6 (305.2)	772.1 (240.6)	603.0 (119.5)
	3	755.8 (147.5)	807.3 (314.0)	604.5 (135.8)
	4	748.0 (183.8)	716.9 (201.8)	670.9 (203.9)
	5	709.9 (165.9)	777.9 (283.1)	631.7 (102.0)
2	1	782.2 (262.4)	830.2 (213.6)	659.8 (155.9)
	2	886.7 (414.6)	718.7 (151.2)	664.4 (132.2)
	3	802.3 (180.1)	787.9 (163.0)	679.5 (160.3)
	4	832.8 (212.6)	815.3 (205.0)	707.3 (211.8)
	5	881.4 (219.6)	829.3 (205.6)	734.6 (201.7)
3	1	722.4 (166.6)	736.8 (132.0)	647.3 (121.5)
	2	740.2 (128.0)	726.2 (172.3)	603.3 (129.9)
	3	758.7 (204.8)	725.3 (195.6)	658.2 (174.0)
	4	753.0 (270.5)	683.7 (118.3)	634.5 (157.8)
	5	851.3 (504.1)	730.7 (172.2)	628.6 (108.5)
4	1	810.1 (229.0)	731.1 (207.5)	643.2 (121.1)
	2	716.8 (223.7)	683.2 (143.2)	549.6 (84.2)
	3	764.9 (239.9)	752.9 (220.0)	636.2 (187.0)
	4	679.8 (129.3)	990.9 (1061.0)	695.7 (253.6)
	5	726.7 (105.6)	720.7 (114.9)	612.0 (135.9)
5	1	864.3 (281.4)	829.1 (203.9)	777.1 (449.0)
	2	795.8 (216.4)	706.9 (177.4)	669.9 (193.4)
	3	884.2 (171.7)	811.7 (199.8)	637.7 (123.1)
	4	908.4 (262.5)	869.3 (270.2)	698.4 (141.5)
	5	539.3 (279.8)	790.2 (220.0)	704.1 (121.8)

END

FIN

6 04 87