THE EFFECTS OF UNDERWATER EXERCISE, NITROGEN NARCOSIS AND EXERCISE-INDUCED HYPERCAPNIA ON PSYCHOMOTOR AND COGNITIVE PERFORMANCE

by

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Abstract

The psychomotor and cognitive performance of ten male divers was assessed during exposure to three effects; underwater exercise, nitrogen (N_2) narcosis and the combined effect of exercise and nitrogen in addition to exercise-induced hypercapnia. The protocol involved rest and exercise, at three sub-maximal workloads on a fin-ergometer in a hyperbaric chamber at simulated underwater depths of 0.5 and 50 m. The control condition was rest at 0.5 m. The test battery included three visual reaction time tests and a sequential short term memory test to assess psychomotor and cognitive performance, respectively. The former included a simple reaction time test (SRT) and two 4-choice tests which differed in that the spatial compatibility of the stimulus-response alternatives was either high (cCRT) or low (iCRT). Short term memory was assessed by determining the accuracy of recall to 6-light sequences (Mem). There was no significant difference in end-tidal carbon dioxide levels ($P_{ET}CO_2$) at 0.5 m. $P_{ET}CO_2$ increased significantly with increased workload at 50 m ($p<0.01$), ranging from 49.7 mmHg at rest to 65.2 mmHg at the highest workload. Results revealed no significant exercise effect on psychomotor or cognitive performance. A significant N_2 effect was identified on psychomotor performance (cCRT and iCRT), with a decrease in speed but not accuracy. Short term memory scores were lower at 50 m indicating a significant N_2 effect on cognitive performance as well. The largest changes corresponded with the exercise-induced hypercapnia at 50 m. A significant interaction effect was identified between reaction time and the combined effect. The slowed reaction time is attributed to a decrease in arousal as explained by the slowed processing model. There was no evidence of a significant interaction effect between short term memory and the combined effect; however the scores were significantly lower at 50 m. Collapsing the performance decrement data across all four tests clearly revealed that the combination of exercise-induced hypercapnia and N_2 narcosis resulted in a significantly larger decrement than the decrement observed with nitrogen alone. A nonlinear relationship was identified between $P_{ET}CO_2$ and performance decrement in all four tests, which has not been reported previously. The relationship provides a means of identifying the susceptibility of diver performance to the combined effects of N_2 narcosis and hypercapnia.

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1.0 Introduction

Research and development in the area of hyperbaric physiology has made remarkable progress in the last fifty years due to the increased interest in the exploration and exploitation of the ocean. The results of the research has meant that a diver can now carry out useful work in the open ocean to depths of 690 msw or 2275 fsw when breathing "trimix". However, despite the depth advances provided by new gas mixtures such as "trimix", their expense, thermal properties and lack of availability are the reasons that compressed air is still used in many diving operations.

When breathing compressed air, the increased partial pressure of nitrogen can produce a behavioural impairment known as narcosis. The impact of narcosis alone is enough to be a central concern to diver safety without even considering the impact when it acts in combination with other potentially hazardous factors.

In the past, hyperbaric research has dealt with the divers' physical capacity, focusing on improving diving equipment and establishing safer exposure limits. However, when working underwater, divers' must use their unique mental abilities in addition to their physical capacities. Lanphier (1967) stressed the importance of both mental and physical performance by stating that "useful activity at any depth requires both mental competence and some ability to do physical work. But, if a choice must be made, physical capacity clearly means little when the brain is disabled." This point was further stressed by Lambertsen (1971) when he stated that, "one of ...a diver's abilities.. is to do physical work and the less this limits his other functions, the better off he is. Provided that he can use his mind and his eye and his thumb, he will be using the main assets man has."

An increase in the partial pressures of the components of air, nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2) may cause such common diving incidents as nitrogen narcosis, decompression sickness, oxygen toxicity and carbon dioxide narcosis. The effects of N_2, O_2 and CO_2 at increased pressure may be modified by a variety of other factors including cold, visibility, anxiety and apprehension, diving experience, alcohol and diver exertion. The list may be expanded; however, the focus of this study is on the combined effects of N_2 narcosis, CO_2 narcosis and diving exertion. To put these factors into perspective, the first step is to predict the limitations they would impose if present alone (Lanphier, 1967) and then attempt to determine their interactions.

A recent review of the literature demonstrated that most researchers have claimed to study a single factor even though other factors may have contributed to, or interacted with, the factor of interest. An example of an interaction of diving-related factors deals with the problem of unexplained loss of consciousness in working divers. The problem itself has been the topic of discussion in diving and medical communities for decades, yet no one has identified its cause or causes (Leitch, 1981).

Morrison et al., (1978) implied that a phenomenon known as CO_2 retention is a major contributing factor in diving accidents which involve a loss of consciousness. The term CO_2 retention describes a form of hypoventilation whereby an individual is supposedly capable of eliminating CO_2 in a normal manner but fails to do so. The result is excessively high alveolar of CO_2, known as hypercapnia (Schaefer, 1958; Lally et al., 1974; Dwyer, 1977; Morrison et al., 1978; Florio et al., 1979; Kerem et al., 1980; MacDonald and Pilmanis, 1981; Morrison et al., 1981; Hickey et al., 1987; Henning et al., 1990). The same sources also documented that a working diver is likely to experience higher than normal alveolar CO_2 levels (P_ACO_2) as a result of the density of hyperbaric air, but a CO_2 retainer may reach dangerously high levels of P_ACO_2. In addition, it has been shown that low ventilatory responses to CO_2 appear to be characteristic of diver populations (Goff et al., 1956; Lanphier, 1963; Lally et al., 1974; Schaefer, 1975; Sherman et al., 1980; and Kerem et al., 1980). The danger lies in the fact that aside from contributing to loss of consciousness, abnormally high levels of CO_2 have also been shown to increase the risk of diving-related incidents of O_2 toxicity, decompression sickness and N_2 narcosis (Lambertsen, 1965; Hesser, 1971; Schaefer, 1974; and Lanphier, 1975).

A recent study by Fothergill (1989, 1991) examined the N_2 and CO_2 components of compressed air narcosis by testing diver performance. The study exposed divers to three ranges of end-tidal CO_2 tensions ($P_{ET}CO_2$) , 30-35 mmHg, 45-50 mmHg and 55-60 mmHg. The study took place in a dry chamber at 0.5 m (1 ATA) and 50 m (6 ATA). Based on the results of a battery of paper and pencil tests, he suggested that inspired CO_2 levels be kept below 3% to avoid the possibility of serious performance deficits at depth. However, as he pointed out, his recommendations did not take into account the involvement of factors such as immersion and workrate, which are present in a real diving situation. Morrison et al. (1981) have shown that $P_{ET}CO_2$ can rise to dangerous levels in excess of 70 mmHg when a diver with low CO_2 sensitivity works underwater at increased pressure.

The underlying physiology of diving-related hypercapnia has been the subject of many studies; however, there is a lack of quantitative data on the interaction of hypercapnia, N_2 narcosis and workrate and their combined effect on diver performance. The majority of the data were obtained from studies which were originally conducted to test decompression schedules or obtain other information. Many of those studies were conducted in a dry chamber and only a few of the studies involved exercise.

1.1 Preliminary Objectives

In response to the lack of data on underwater performance at raised ambient pressure, this study proposed to

1. improve the current level of understanding of the effects of levels of underwater exercise at 0.5 m (1 ATA) on psychomotor and cognitive measures,
2. contribute to the wealth of knowledge of the effects of nitrogen narcosis on diver performance by applying familiar testing methodologies in a realistic diving environment at a depth of 50 m (6 ATA) and
3. determine quantitatively the combined effects of nitrogen narcosis and exercise-induced hypercapnia on the psychomotor and cognitive performance of divers at 50 m (6 ATA).

2.0 Literature Review

The physical demands of diving have been studied extensively. However, there has been considerably less research devoted to the psychomotor and cognitive demands of performing work in an underwater environment.

2.1 An Overview of Narcosis

Many divers working in open water depths beyond 30 m (100 ft) have experienced feelings of euphoria, with signs and symptoms of confusion, neuromuscular in-coordination and decrements in performance (Adolfson, 1967; Bean, 1950; Behnke, 1965; Case and Haldane, 1941; Hesser et al., 1971; Bennett, 1982). Collectively, the sensations and feelings are known as compressed air narcosis. The term narcosis itself refers to "a reversible depression of function of an organism" (Fowler, 1985).

2.1.1 The Signs and Symptoms of Narcosis

It has been shown that the traditional signs and symptoms of narcosis may begin while breathing air during dives to 20 m (66 ft) (Behnke et al., 1935), but most of the symptoms are mild and many divers do not notice any effects until 30 m (100 ft). At depths beyond 91 m (300 ft), the effects are severe and may include impaired muscular activity, stupefaction and possible loss of consciousness (Bennett, 1982). Between 30 and 91 m, the responses vary considerable between different divers and even between the same diver on different days. These variances make it difficult to develop reliable safety limits for hyperbaric work.

2.1.2 A History of Narcosis Incidents

Some of the earliest reported cases of narcosis occurred before the turn of the century. In 1835, Junod noted that when breathing compressed air "the functions of the brain are activated, imagination is lively...and in some persons, symptoms of intoxication are present" (cf. Bennett, 1966). A report by Green (1861, cf. Bennett, 1966), which referred to feelings of sleepiness, hallucinations and impaired judgment, advised immediate return of the diver to the surface.

The danger of narcosis stems from the diver's inability to recognize changes in his/her behaviour before the physiological system deteriorates to a critical state, with little or no recall of the episode after the exposure. There have been numerous accounts of narcosis in the literature, with divergent opinions on the cause or mechanisms.

2.1.3 Theories of Compressed Air Narcosis

Theories on the cause of compressed air narcosis range from increased partial pressure of O_2, N_2 and CO_2, to increased pressure *per se*, and even to the involvement of claustrophobia and anxiety (Bennett, 1966).

The earliest speculation about the sensations resulting from air diving was the theory of pressure *per se* (Junod, 1835; Moxon, 1881 cf. Bennett, 1966). This was quickly disregarded when it was established that narcosis is a function of the nature of the gas breathed in addition to the partial pressure of the gas (Bennett, 1982). A theory was proposed by early caisson workers who attributed narcosis to psychological factors such as latent suppressed claustrophobia (Hill, 1933). However, the information that disproved the pressure theory also failed to support their hypothesis. Subsequently, the nature of the gas was considered.

At first, it was believed that high O_2 tensions were responsible (Birch, 1859; Bert, 1878; Binger et al., 1927; Damant, 1930; Smith et al., 1932 c.f. Bennett, 1982). This theory was discarded when it was understood that O_2 was toxic however, subjects breathing pure O_2 at 10 m (33 ft) experienced none of the sensations encountered by divers breathing air at 91 m, (300 ft or equivalent O_2 partial pressure (P_{O_2}) of 2 ATA) (Bennett, 1982). It has since been established that O_2 does have synergistic properties (Frankenhaeuser et al., 1963; Hesser, 1963) and there is still speculation as to whether this is due to above-normal CO_2 levels or to O_2 itself (Fenn, 1965).

Behnke, Thomson and Motley (1935) were the first to attribute narcosis to the raised partial pressure of N_2; a physiologically inert gas. During dives to 20 m and 30 m (3 and 4 ATA), they observed "euphoria, retardment of the higher mental processes and impaired neuromuscular coordination". They also noted a reduction in accuracy on performance tests such as arithmetic and recording data, as well as delayed responses to various modes of stimuli. Behnke and Willmon (1939) concluded that "the narcotic action of inert gases is related to the solubility of the gas in the lipid substances of the central nervous system". The findings of Behnke and Willmon were confirmed by Case and Haldane (1941), who noted that small fractions of CO_2 in the air at increased ambient pressure also had distinct effects on psychomotor performance.

In the early days of diving research, a number of incidents occurred that led scientists to suggest that CO_2 played an important role in narcosis; however, there was uncertainty regarding the level of involvement. In addition to their work on N_2, Behnke and Willmon (1939) also noted the apparent effects of CO_2 on narcosis during the salvage of the U.S.S. Squalus. They observed mental disturbances in divers working at 72 m (240 fsw or 8.3 ATA). Since the symptoms were of an unusually severe nature, Behnke and Willmon suggested that the accumulation of CO_2 in the diver helmets may have interacted with the compressed air narcosis, thereby exacerbating the narcosis that the diver experienced. Case and Haldane (1941) reported similar findings and suggested that although it was unlikely that CO_2 was responsible for compressed air narcosis, the enhancing effect of CO_2, when some degree of narcosis is present, required further study (Case and Haldane, 1941; Lanphier, 1963).

The apparent ability of CO_2 to augment narcosis led some researchers to attempt to explain narcosis simply as a case of CO_2 intoxication. Bean (1950) suggested that narcosis was due to hypercapnia, or elevated levels of $P_{ET}CO_2$, caused by increasing gas density which impaired ventilatory response. Similar views were held by Seusing and Drube (1960), Bühlmann (1963) and Vail (1971). However, experiments by Rashbass (1955) and Cabarrou

(1959, 1964, 1966), which compared P_ACO_2 with quantitative measurements of narcosis, did not support the carbon dioxide theory. A study by Bennett (1964, 1965), using auditory evoked potentials, showed that there was no correlation between CO_2 retention and the degree of narcosis. At the time, this was accepted as conclusive evidence against the CO_2 theory; however, Fowler and Ackles (1977) have since stated that the evoked response is not a valid measure of narcosis. Therefore, the debate as to the level, extent and involvement continues.

2.2 Causes and Mechanisms of Inert Gas Narcosis

It is now widely accepted that narcosis can be induced by the inert gases which make up a subgroup of the gaseous and volatile anesthetics (Meyer and Hopff, 1923). This is where the term "inert gas narcosis" is derived. It describes the signs and symptoms of narcosis brought on by breathing inert gases. This subgroup of gases includes xenon, krypton, argon, nitrogen, neon and helium, in addition to hydrogen, nitrous oxide, cyclopropane and ethylene. Although not all of the gases are truly inert, they are all non-toxic to physiological systems and those that are narcotic cause the same behavioural effects yet differ in their potency (Bennett, 1966).

Narcotic potency refers to the relative partial pressure of the gas in the breathing mixture that is required to produce a given effect (Fowler, 1989). In order for argon, nitrogen and hydrogen to be narcotic, they must be breathed at pressures greater than ambient pressure. Nitrogen can induce narcosis at approximately 3 ATA however, argon and hydrogen become narcotic at considerably higher pressures. In contrast, neon and helium are non-narcotic. Helium may be used as a substitute for nitrogen to prevent narcosis, but it is expensive, lowers core temperature and its voice-distorting properties make communication difficult. For these reasons, compressed air continues to be used in diving to depths less than 50 m and as a result, the impairment caused by narcosis remains as an important safety concern (Shilling et al., 1976; Diving Operations at Work Regulations, 1981).

The risk of using compressed air is increased by the raised partial pressure of O_2 or CO_2, which can influence the onset and severity of narcosis and hence performance underwater at depth. Hyperoxia and hypercapnia have both been shown to contribute to the narcosis, either directly or indirectly, by interacting with or modifying the effect of nitrogen (Hesser et al., 1978). It is the latter, hypercapnia, which is of concern in this study.

2.3 Hypercapnia and Divers

It is well established that elevations in the alveolar partial pressure of CO_2 (P_ACO_2) occur with hyperbaric work as a result of an increase in ambient pressure and/or diver workrate (Jarrett, 1966; Salzano et al., 1970; Kurenkov, 1973; Linnarsson et al., 1974; Fagraeus, 1974; Lanphier, 1975; Wood et al., 1976; Spaur et al., 1977; Fagraeus and Bennett, 1978; Thalman et al., 1977; Morrison et al., 1978; MacDonald and Pilmanis, 1981; Morrison et al., 1981; Hickey et al., 1987).

The measurement of $P_{ET}CO_2$ (or P_ACO_2) has been used as an estimate of arterial CO_2 tension (P_aCO_2)(Jones et al, 1979). The normal resting range for $P_{ET}CO_2$ is 35-40 mmHg (Lanphier, 1975), but values greater than 70 mmHg have been reported during various dive activities (Lanphier, 1955, 1963; Morrison et al., 1981; Taylor, 1987). Definite signs of CO_2 toxicity or intoxication are usually evident at $P_{ET}CO_2$ levels of 60 mmHg or greater (Lanphier, 1975). It has been suggested that a diver's susceptibility to incidents of O_2 toxicity and N_2 narcosis is enhanced even at $P_{ET}CO_2$ levels of 50 mmHg (Slonim and Bender, 1974; Lanphier, 1975; Schaefer, 1974; MacDonald and Pilmanis, 1981). The danger of hypercapnia is further increased in divers who have a tendency to retain CO_2.

2.3.1 CO_2 Retention

CO_2 retention is a term which has been used to describe individuals who hypoventilate or have a reduced ventilatory response to CO_2 (Lanphier, 1955). Though these individuals are supposedly capable of eliminating CO_2 in a normal manner, they fail to do so, resulting in excessive levels of CO_2 (Morrison et al., 1981). As reviewed by Lanphier and Camporesi (1982), CO_2 retention is the result of three factors: 1) elevated inspired O_2 pressure; 2) increased work of breathing due to high gas density and breathing apparatus limitations; and 3) an inadequate ventilatory response to exertion. It is the risk of CO_2 narcosis, especially in situations when the possibility of inert gas narcosis exists, that could render heavy work at raised ambient pressures extremely hazardous (Miller et al., 1971).

2.3.2 A Review of Diving and Hypercapnia Research

Although there have been numerous studies on hypercapnia and diving, the conditions under which the studies took place vary considerably with respect to ergometry and environmental conditions. Two modes of ergometry were generally used: fin-swimming and cycle. The workrates varied considerably, from moderate to supramaximal (i.e. workloads which induce exhaustion within 3-5 minutes at 0.5 m (1 ATA); (Linnarsson and Fagraeus, 1976). Dry chamber environmental conditions ranged from 20 m (3 ATA) (Behnke, Thomson and Motley, 1935) to 90 m (10 ATA) (Case and Haldane, 1941), while underwater exposures ranged from 0.5 m (1 ATA) (Lanphier 1955, 1963) to 58 m (6.8 ATA) (Hickey et al., 1987).

The lack of standardization in experimental conditions makes it difficult to quantify the combined effects of pressure and workrate on $P_{ET}CO_2$ levels. Table 2.1 outlines the range in experimental conditions by listing various modes of ergometry, environmental conditions and the resultant mean and maximal $P_{ET}CO_2$ levels from a number of studies which investigated the effects of pressure and exercise on CO_2.

Most of the earlier hyperbaric studies were done under dry conditions due to the problem of water ingress into the equipment when working underwater. Miller et al., (1971) studied the cardiorespiratory responses of divers working in a dry chamber, at 68 m (7.8 ATA). They noted that the mean $P_{ET}CO_2$ level was approximately 50 mmHg when exercising on a bicycle ergometer at submaximal workloads. Linnarsson and Fagraeus (1976) used supramaximal workloads on a bicycle ergometer to study maximal oxygen uptake at five different ambient pressures in a dry hyperbaric chamber. Their results showed higher CO_2 levels than those of Miller et al. (1971); the mean $P_{ET}CO_2$ value was 55 mmHg at 50 m (6 ATA). All of the 8 subjects experienced progressive dyspnea at that depth and three subjects also reported dizziness, vertigo and visual disturbances, with mental and sensory disturbances also noted at approximately 2.5 minutes into the testing phase of their experiment.

Table 2.1 A review of the hyperbaric studies of exercise and $P_{ET}CO_2$ at normal and raised ambient pressure.

Study	Depth m (ATA)	Condition	Ergometry	Workrate	Mean $P_{ET}CO_2$ (mmHg)	Maximal $P_{ET}CO_2$ (mmHg)
Miller et al. (1971)	68 (7.8)	Dry	Bike	Submax.	50	---
Linnarsson and Fagraeus (1976)	50 (6.0)	Dry	Bike	Maximal	55	---
Lanphier (1963)	0.5 (1.0)	Wet	Fin	Submax.	47	53
	30 (4.0)	Wet	Fin	Submax	55	>70
Hickey et al. (1987)	58 (6.8)	Wet	Bike	Submax.	50	54
MacDonald and Pilmanis (1981)	30 (4.0)	Wet	Bike	Maximal	54	65
Taylor (1987)	50 (6.0)	Wet	Bike	Maximal	63	72
Morrison et al. (1978,81)	50 (6.0)	Wet	Bike	Submax.	55	76

Note: Maximal workrates indicate that the subject exercised to exhaustion.

Lanphier (1955, 1963) conducted a number of studies on the respiratory responses to hyperbaric exposure using various breathing gas mixtures. In one of the conditions, $P_{ET}CO_2$ was measured in 10 men doing moderate exercise underwater on a "swim-ergometer" while breathing air at 0.5 m (1 ATA). The mean $P_{ET}CO_2$ level reported was 47 mmHg, with a maximum value of 53 mmHg. For such near-normal conditions, the mean value was unusually high, while the maximum value was definitely abnormal and was attributed to one of the "high CO_2" men. Lanphier also measured respiratory responses to exercise at 30 m (4 ATA) with a nitrogen-oxygen breathing gas mixture (55% N_2 - 45% O_2). The results of these trials showed mean $P_{ET}CO_2$ values of approximately 52-55 mmHg and a maximal value exceeding 70 mmHg (Lanphier, 1963).

Some of the more recent studies have reported higher levels of CO_2 accumulation in working divers (Dwyer, 1977; MacDonald and Pilmanis, 1982). Hickey et al., (1987) measured respiratory function in divers underwater at 58 m (6.8 ATA). The divers exercised upright, on a cycle ergometer, at submaximal workrates. Their findings showed mean $P_{ET}CO_2$ values of 50 mmHg with maximal values of 54 mmHg. MacDonald and Pilmanis (1981) took a different approach to measuring CO_2 levels during underwater work. The goal of their study was to determine the $P_{ET}CO_2$ levels in experienced scuba divers during open-ocean activities. Using specialized equipment, they reported a range of values from 54 to 65 mmHg, corresponding to the most and least CO_2 sensitive individuals, respectively. The values they reported were for maximal exercise on a cycle ergometer at 30 m (4 ATA). The results from a chamber study by Taylor (1987) matched the open-ocean results of MacDonald and Pilmanis (1981). Taylor (1987) reported a mean $P_{ET}CO_2$ value of 63 mmHg during submaximal cycle ergometry at 50 m (6 ATA) in the wet-pot of a hyperbaric chamber.

Incidents of $P_{ET}CO_2$ levels above 70 mmHg have been recorded in experimental dives using an underwater cycle ergometer at depth (Morrison et al., 1978, 1981). One of the divers, who was found to have an extremely low ventilatory response to exercise, demonstrated severe hypoventilation and hypercapnia. The diver's ventilation was 25-50% lower than that of the other divers and his $P_{ET}CO_2$ reached a hazardous level of 76 mmHg. The results of these studies led to the conclusion that divers who possess a natural tendency to retain CO_2 during underwater work may be particularly at risk from the combined effects of hypercapnia and compressed air narcosis (Morrison et al., 1978, 1981).

2.4 The Nature of CO_2 Interaction with N_2 narcosis

One of the best descriptions of the enhancement of inert gas narcosis by CO_2 is a personal account by Lanphier (1963) that occurred while he was testing a new bicycle ergometer. The experiment took place in a dry chamber at 68 m (7.8 ATA) and involved exercise at moderate workloads. Unfortunately, Lanphier was using a breathing system that supplied only about half of his respiratory needs, and the normal symptoms of narcosis quickly progressed into a coma within 3 minutes of commencing exercise. As a result of his life-threatening experience, he stated that "narcosis itself will be the primary limiting factor and that its potentiation by CO_2 will become a problem in situations when more than minimal exertion is attempted."

Hesser and colleagues have been involved in studying the role of CO_2 in compressed air narcosis for more than 25 years. In 1971 they studied the role of CO_2 and N_2 in compressed air narcosis by relating performance to changes in the alveolar partial pressures of CO_2 and N_2 when P_{O2} was kept constant. Their work was the first to attempt a quantitative evaluation of the combined effects. However, it did not succeed in establishing a clear relationship. They continued their research with a series of experiments which analyzed compressed air narcosis based on the individual and combined roles of CO_2, O_2 and N_2, as measured by diver performance (1978). Their results implied that a rise in $P_{ET}CO_2$ of 10 mmHg resulted in an impairment of approximately 10% in both mental and psychomotor functions. In addition, their results suggested that all three gases exhibited narcotic properties at increased ambient pressure but that the mechanisms of CO_2 and N_2 narcosis differ (Hesser et al., 1978). This view is supported by the results of Fothergill et al. (1989, 1991). Based on differences in intratest results for N_2 and CO_2, Fothergill concluded that the underlying physiological mechanism of CO_2 narcosis is different from that of N_2 narcosis.

2.4.1 Thresholds for CO_2 Narcosis and N_2 Narcosis?

One of the techniques frequently used in formulating relationships between factors is to establish whether a threshold exists, whereby beyond some point an effect is present. This approach has been used by researchers studying N_2 narcosis and CO_2 narcosis. There is some agreement that beyond 30 m (100 ft) the majority of individuals experience a base level of symptoms typical of nitrogen narcosis (Bennett, 1982). Subjective intoxication has been observed at depths as shallow as 3 ATA (Behnke, Thomson and Motley, 1935) while objective changes in performance have been noted at 4 ATA (Kiessling and Maag, 1960; Poulton et al., 1964). Recent work by Fowler et al (1989) concluded that beyond 50 m a diver is likely to exhibit impaired performance due to N_2 narcosis. However, they did not identify 50 m as a threshold for narcosis. The results reviewed so far are inconclusive as to whether a threshold for N_2 narcosis exists.

The issue of a threshold for CO_2 narcosis is still under debate. Hesser et al. (1978) reported that the involvement of CO_2 in impairment of mental function is negligible as long as P_ACO_2 does not exceed 40 mmHg at depth. Sayers et al. (1987) established a higher threshold of 51 mmHg as the level above which effects on a reasoning task were apparent.

A study by McAleavy et al. (1961) provided evidence against a threshold based on a linear relationship between anesthetic potency of N_2O and P_ACO_2 in the range of 20 to 60 mmHg. Schaefer (1974) was in agreement with a lack of threshold contending that different areas of the brain have different sensitivities to CO_2. More recently, Fothergill (1989, 1991) presented results which provided further evidence against a common threshold for all behavioural and/or performance effects. He suggested that if a threshold does exist it would be dependent on the sensitivity of the particular task or cognitive factor to excessive CO_2 tensions.

2.5 Definitions used for Describing Factor Interaction

It is important to study the effects of diving-related factors on performance, but there is confusion with the terminology, methodology and interpretation of how the factors may act together. In describing factor interaction, one should specify the direction and size of the effect (Fowler et al., 1985).

With respect to direction, the term impairment refers to a factor which when combined with narcosis, causes a further deterioration in performance beyond that which is attributed to the narcosis. Alternatively, the term improvement describes a factor that reverses the effects of narcosis on performance (Fowler et al., 1985). Exercise is an example of a factor that has been shown to have an improvement effect when other factors are not present (Adolfson, 1965; Davey, 1974; Bradley and Dickson, 1976).

When referring to the size of the effect, the accepted applicable terms are antagonism, addition and synergism (Miller and Miller, 1976). The three terms refer to a combined effect with narcosis that is proportionately less than, equal to, or greater than the sum of the separate effects of the factor and narcosis, respectively. These terms are not used when describing anything about the underlying causal mechanisms of narcosis. For this purpose, potentiation and amelioration, corresponding to impairment and improvement, respectively, are used to imply that a factor modifies narcosis through a common underlying mechanism (Fowler et al., 1985).

A number of factors may modify narcosis, including fatigue, hard work (Adolfson, 1965), apprehension and anxiety (Davis et al., 1972), CO_2 retention (Hesser et al., 1971, 1978; Fothergill, 1989) and ethanol (Fowler et al, 1985). According to Fowler and co-workers, ethanol is the only factor for which there is conclusive evidence that it potentiates inert gas narcosis (Jones et al., 1979; Alkana and Malcolm, 1982; Bennett, 1982; Hamilton et al., 1984). The remaining factors are believed to affect the size of the narcotic effect as there is a lack of conclusive evidence supporting modification through a common mechanism (Fowler et al., 1985).

2.6 Measuring Diver Performance

In describing an effect, a qualitative change refers to the pattern of behavioural changes that a gas produces. The classic description of narcosis provides some background into this pattern, with subjective descriptions such as euphoria and confusion (Behnke and Willmon, 1939); however, such descriptions are inexact and defining behaviour in itself provides numerous problems. An alternative to observing the behavioural effects of narcosis is to measure the electrical activity of the brain.

Bennett (1966) studied the changes in mental state with exposure to elevated pressure using the techniques of electroencephalogram (EEG), evoked potentials and the flicker fusion frequency (F.F.F.) (Bennett and Cross, 1960). He defined the nitrogen threshold as the time required, at any given pressure, to abolish alpha blocking and noted that there was a fundamental change in the central nervous system when a certain tension of nitrogen was exceeded (Bennett 1958). When he studied the effect of inert gases such as nitrogen and argon on induced evoked potentials, he found that brain synapses were affected in a manner similar to spinal synapses. Hence, applying his findings to those of Lindsley (1958), he suggested that the reticular formation of the central nervous system was especially sensitive to raised pressures of inter gases due to the large number of synapses involved. However, while providing useful information on the mental activity of the individual, the EEG and evoked potentials do not provide information of the actual change in diver performance and are cumbersome to use as a selection criteria for divers.

While underwater, a working diver may be engaged in an array of activities ranging from salvage, rescue, search and recovery operations to inspection, maintenance and construction jobs (Reilly and Cameron, 1968). Although the activities listed are quite general, Reilly and Cameron found that they could represent them within certain categories of human performance which were common to the specific jobs. The categories included visual surveillance and navigation, work production, information retrieval, information processing and decision making. The categories encompass a wide range of activities which a diver is responsible for carrying-out underwater and, as a result researchers have developed a wide range of tasks to assess performance within the various categories.

Traditionally, researchers have relied on "paper and pencil" tests in combination with manual dexterity tests to assess cognitive and psychomotor aspects of diver performance. Examples of tests which have been used during diving research to assess cognitive ability include a variety of arithmetic tests, the Stroop color decision test, the digit symbol test and an assortment of memory tests. A range of tests has also been designed to assess psychomotor ability under hyperbaric conditions, including the ball bearing test, the Purdue Pegboard test, the Bennett hand tool dexterity test (BHTDT) and an assortment of reaction time tests. Traditional "paper and pencil" tests can be modified for underwater use by using grease or waterproof (wax) markers on a slate or white-board. Of the other tests listed above, only the digit symbol test, the Purdue Pegboard and the BHTDT have successfully been adapted for underwater use (Adolfson and Berghage, 1974).

2.6.1 Reaction time tests

One way of studying performance is to assess motor performance efficiency. Tests of motor performance generally fall into two categories: response outcome measures and response production measures (Magill, 1989). The former category includes one of the most common forms of psychomotor performance tests, the reaction time test, which considers the temporal aspects of information processing (Schmidt, 1988). The main measure of the individual's behaviour is the time interval between the presentation of a stimulus and evocation of a response. It is presumed that many information processing activities occur during the time interval. The object is to observe the change in reaction time as a result of some influencing variable or factor.

It is believed that there are at least three stages of information processing that intervene between the presentation of the stimulus and the evocation of the response (Schmidt, 1988). The three stages include stimulus-identification, response-selection and response-programming. If it is assumed that the initial step in information processing is the presentation of a stimulus, then during the first stage, the individual may or may not acknowledge that stimulus. If the stimulus is acknowledged then the result of the first stage is believed to be some representation of the stimulus, which is then passed on to the next stage; response-selection (Schmidt, 1991). Since the stimulus-identification stage is dependent on the nature of the stimulus itself, it may therefore be affected by the clarity and intensity of the stimulus. The clarity refers to the "sharpness" of the stimulus while the intensity refers to as an example, the "brightness" of the stimulus. Reaction time is shortest when the stimulus is focused and bright (Schmidt, 1988).

During the second stage of information processing, the individual must choose whether or not they will respond and what type of a response to make. At this stage, the processing may be affected by the number of stimulus-response (S-R) alternatives and/or the compatibility of the stimulus and the response. One of the most important findings in the area of motor control was by Hick (1952) who studied the relationship between reaction time and the number of S-R alternatives. The results of his research indicated that the relationship was clearly linear when the number of S-R alternatives is converted to a log base 2, that is, there was a constant increase in reaction time as the number of S-R alternatives doubled. The compatibility of the S-R complex has also been shown to affect reaction time, with an increase in reaction time noted with increasing incompatibility (Fitts and Seeger, 1953). An example of a highly compatible S-R complex would be when two response buttons are situated directly below two lights and the individual is to respond to the button directly below the light. The set-up described would be referred to as incompatible if the individual responded by pressing the other button (opposite) rather than the one directly below it.

Information processing in the response-selection stage can also be affected by practice. Research has shown that for a given number of S-R alternatives, the more extensive the amount of practice, the shorter the reaction time (Schmidt, 1991). This finding has been demonstrated for an increase in S-R alternatives from two to four (Mowbray and Rhoades, 1959). Mowbray and Rhoades (1959) found that when subjects completed more than 13 practice trials of 3000 stimuli, there was practically no difference in reaction time between two-choices and four-choices tests. They suggested that with sufficient practice, the similar findings may be seen for any reasonable number of stimuli. However, they also stated that at some point in time, even a lifetime of practice may not be sufficient to reach a physiological limit.

The last stage is the response-programming stage, where the individual prepares his/herself for the response by initiating and carrying-out the actions required. The final stage may be affected by the complexity of the response. Henry and Rogers (1960) conducted some of the earliest work in the area of response-programming when they studied the nature of movements made in response to a simple reaction time paradigm. Within their study, they used the same stimulus while considering three different response movements. The responses ranged from simple movements such as lifting a finger, to complex movements such as a double ball strike. Their results indicated that the more complex the response is, the greater the amount of time that is required to prepare and program the actions.

The above descriptions of the three stages indicate that each of the three stages of information processing involves different kinds of processing which may by affected by a variety of factors or variables.

2.6.2 Short term Memory

When working underwater, a diver is often faced with trying to retrieve information from memory. Whether he is recalling his decompression limits and schedule, or information relevant to the task he is carrying out, his ability to recall is important. Posner (1969) defined three types of memory which deal with the short term storage of information (the inclusion of long-term memory would make up a fourth type): short-term sensory; short term information storage; and short term operational storage ("working" memory).

The first type refers to a brief exposure (1 sec) to many items where the individual is capable of recalling much less information than is available. The second type re-codes some of the information from the original sensory impressions, and assigns the information a representative code so that it may be retained for at least a short time (20-30 sec). The third type is concerned with the short term storage of information retrieved from long term memory (Marteniuk, 1976).

Of the three types of short term memory, type 2 provides the least capacity and serves as a bottleneck for the passage of information between the environment and long term memory. It follows that to assess short term memory, a test should assess the ability to recall information within 20-30 seconds of presenting the information. One of the areas of interest, when studying memory, is the limitations that memory imposes on the processing of information in terms of how much information can be accurately processed in a given time.

2.6.3 Information processing

There is continued debate on how to approach the analysis of narcosis. Fowler et al. (1985) outlined four approaches and provided a comprehensive review of the studies which contributed to their development. These four approaches are outlined below:

(a) The descriptive model,

(b) The hierarchical organization hypothesis,

(c) The operant paradigm and

(d) The slowed processing model.

The review stressed that there is a lack of quantitative data on narcosis and performance decrements. In this context, the term quantitative refers to the partial pressures of the gases required to produce some specified change (Fowler et al., 1985). It is the quantitative effects of exercise, N_2 narcosis and hypercapnia on diver performance that concerns this study.

2.6.4 Performance aspects of Exercise

One of the few researchers to consider the effects of exercise on diver performance was Dr. J. Adolfson. In the late sixties (1965, 1967), he conducted two studies which investigated the effects of moderate exercise on performance as measured using cognitive and manual dexterity tests, at 30, 60 and 90 m (4, 7 and 10 ATA), while breathing air. His results indicated that manual dexterity deteriorated with exercise but there was no significant decrement in the mental arithmetic test. The effects on dexterity were attributed to high CO_2 levels, even though they were not measured and the absence of a significant effect on mental arithmetic suggested that exercise directly disturbed dexterity (Baddeley, 1971). In fact, going to 30 and 60 m, the results showed improvement in mental arithmetic. This would suggest that exercise served to "stimulate wakefulness" and counteract the effects of N_2 narcosis. This suggestion is consistent with the belief that exercise increases the level of arousal (Davey et al., 1974; Fowler et al., 1985); however, the facilitating effects are believed to be short-term (Tomporowski and Ellis, 1986).

Tomporowski and Ellis (1986) offered a comprehensive literature review of the effects of exercise on cognitive function and motor performance. There are two competing explanatory models for the effects of physical arousal on performance: the inverted-U hypothesis which was first proposed by Yerkes and Dodson (1908) and has since been expanded by a number of others, and the drive-theory hypothesis, as proposed by Spense and Spense (1966).

The inverted-U hypothesis states that as physical arousal increases, performance is likely to improve up to an optimal point and beyond that point any further increase in arousal brings about a deterioration in performance (Martens, 1974). Support for the inverted-U hypothesis has come from various studies using various tests: Levitt and Gutin (1971) used a multiple choice reaction time test; Davey (1974) used a test of short term memory (Brown and Poulton test of attention); and Sjoberg (1977) also used reaction time tests.

In contrast to the inverted-U hypothesis, the drive-theory hypothesis suggests that an increase in physical arousal should facilitate performance in a linear manner (Spense and Spense, 1966). Experimental work by Spense (1971) and Landers (1980) has lent support for the drive-theory hypothesis. However, the debate over the models is long-standing and continues.

The review by Tomporowski and Ellis (1986) outlined a number of shortcomings in the research on exercise and performance, stating that most of the studies up to that point had focused on the relation between anxiety states and motor performance rather than exercise and cognitive abilities. More recently, theories of attentional process have been used to help explain how information processing influences motor and cognitive tasks. It is generally accepted that physical arousal influences attention and the model that has been used as the prototype to describe the process was proposed by Easterbrook (1959) . The theory basically states that an increase in arousal results in a shift or narrowing of attention to the parts of a task which are central to correct performance . Despite acceptance of the basic arousal theory and its relation to performance, there are still problems with defining and measuring the arousal state. The review by Tomporowski and Ellis (1986) also concluded that the research done on the effects of exercise on mental function was population specific, lacked standardized methodology and failed to provide clear evidence for the relationship between exercise and cognition.

2.6.5 Performance aspects of N_2 narcosis

The effects of hyperbaric pressure on diver performance were studied as early as 1935 by Behnke, who listed the progression in symptoms up to 91m. The area of study was continued by Shilling and Willgrube (1937) in their study, which is accepted as the first study to quantify the properties of compressed air. Since that time, the general consensus is that of an increasing decrement in performance with increasing air pressure (Bennett, 1982). Despite the early start in the area of research, analysis of the effects of N_2 narcosis on performance is still currently under debate.

Traditionally, most studies have attempted to develop, then employ, tests which best assess, or are most sensitive to narcosis. This approach is similar to that of the descriptive model and the hierarchical organization hypothesis (Fowler et al., 1985). Based on this approach, the general consensus is that cognitive tests show the greatest decrement, manual dexterity tests show the least, and increases in reaction time lie somewhere in between (Fowler et al., 1985). From these results, the effects of narcosis on performance have been related to the level of mental processing, with cognitive and reaction time tests representing a higher level and manual dexterity a lower level. A relationship between the degree of the performance impairment and the complexity of the test was noted by Kiessling and Maag (1962).

The operant paradigm and the slowed processing model provide alternative ways of studying narcosis. The operant paradigm is a measurement technique that allows complex behavior to be assessed while manipulating narcosis, pressure, or other variables. The measurement technique uses different schedules of reinforcement to produce different patterns of response. In light of the safety concerns of exposing humans to the effects of deep saturation diving and the difficulties of designing such experiments, this technique is ideal to use with animals. However, is unacceptable with humans (Fowler et al., 1985). The slowed processing model approaches narcosis by asking why performance breaks down on a test, rather than considering the test itself. Since the latter approach is the main focus in the majority of recent narcosis research with humans, it will be discussed in greater detail (Fowler et al., 1985, 1987, 1989; Hamilton et al., 1989; Fothergill, 1989).

In the slowed processing model, performance is explained in terms of an information processing system which is based on three features. The first is a series of stages known as structural variables. The individual variables describe the type of processing they perform. The second feature is a functional variable which is based on the view that overall efficiency is determined by the level of arousal. Finally, there are strategic variables which include the control processes that organize the system's resources so that it may accomplish a given task (Fowler et al., 1985). When the slowed processing model is applied to performance test results, the slowing due to N_2 narcosis, as measured by reaction time tests, is best accounted for by a decrease in the system's efficiency and is therefore attributed to a functional change (Fowler and Granger, 1981; Fowler et al., 1983). A study by Hamilton, Fowler and Porlier (1984) concluded that narcosis decreases the level of arousal or activation of the central nervous system and it is this decrease in arousal that increases reaction time.

Recently, Fowler and his colleagues (1989) suggested that the decrease in arousal affects information processing via an early gating mechanism. As a result, the slowing noted in performance is not localized to a specific stage of information processing, and the behavioural effects of narcosis that appear complex are believed to be due to secondary changes in task strategy. Typically, N_2 narcosis has been shown to bring about a slowing in response time and an decrease in the accuracy of performance. Fowler et al. (1989) demonstrated that the decrease in accuracy can be controlled for with appropriate training. If accuracy is not controlled for, the increased number of errors noted is associated with a shift in the speed-accuracy trade-off, which represents a change in strategy.

2.6.6 Performance Aspects of CO_2 Narcosis

The literature on the effects of CO_2 on psychomotor and cognitive performance is limited. There is increased awareness of the potential for above normal levels of inspired CO_2 tensions in industries using submarines, confined vehicles and in any job which uses a re-breathing apparatus. However, despite the awareness of CO_2 and its anesthetic properties, research on the effects of hypercapnia on performance is an area that has received little attention.

In the mid-Nineteenth Century, Hickman discovered and used the anesthetic effect of CO_2, primarily on animals, then in 1927, Walters (cf. Bennett, 1966) used the anesthetic properties of 30% CO_2 to perform minor surgery on two women. Unfortunately, both women convulsed after wakening, so Walkers did not continue his research on CO_2.

In 1961, a group of researchers led by McAleavy devised a method of determining the anesthetic potency of CO_2 by titrating CO_2 against nitrous oxide (N_2O). Their protocol required human subjects to perform a coordinated task while slowly changing the inspired level of N_2O. The level of N_2O was increased or decreased to a point where coordination failed to an arbitrary degree, which in the end turned out to coincide with loss of consciousness. McAleavy then varied the inspired CO_2 level and the N_2O level until the loss of coordination end-point. He found that higher levels of N_2O were required with lower CO_2 levels, while the opposite was true with high CO_2 levels. A regression equation of the relationship revealed that CO_2 has five times the anesthetic potency of N_2O.

Sheehy and his co-workers (1982) conducted a study to assess the effects of increased P_ICO_2 tensions on auditory reaction time and short-term memory tests. Their results indicated that reaction times were significantly higher when F_ICO_2 levels were above 5%, but there were no effects on short term memory when using digit and letter span tests. Unfortunately, there results were based on only 6 subjects in a group and different groups were used for the reaction time and memory tests. In addition there was no mention of the end-tidal or alveolar CO_2 tension, which must have varied among the subjects.

Sayers et al. (1987) measured the effects of CO_2 levels between 0 and 7.5% on a reasoning task and on short-term memory. Their results implied that capacity for reasoning is likely to deteriorate if untrained subjects work in air containing CO_2 levels above 5.5% at sea level. Their results support those of Sheehy et al. (1982), in that they also did not note any significant impairment of memory processes.

Some of the most recent work on the effects of hypercapnia on performance was conducted by Henning and colleagues (1990). Their study exposed divers to 6% CO_2

mixtures under normobaric conditions and then returned them to air breathing to measure the post-exposure effects. The test battery consisted of simple and choice reaction time, postural sway, tremor and hand steadiness. During the exposure to CO_2, only the reaction time tests were conducted due to the movement artifact caused by increased ventilation. Contrary to the findings of others, their results showed that there were no significant performance decrements during the exposure. However, their results only reported the mean reaction times and did not include any mention of the error scores. Therefore, it is possible that the subjects altered their task strategy by sacrificing accuracy to maintain speed.

Fothergill and colleagues (1989, 1991) conducted a study which examined the effects of a range of end-tidal P_{CO2} tensions on a variety of tasks. The levels of CO_2 were regulated by a re-breathing circuit so that the $P_{ET}CO_2$ tensions fell within the range of 30-35 mmHg, 45-50 mmHg and 55-60 mmHg. Their results led them to conclude that $P_{ET}CO_2$ tensions above 47 mmHg significantly impaired both cognitive and psychomotor performance. They explained their findings using the slowed-processing model (Fowler, 1985) and concluded that the decrements in performance noted with hypercapnia were due to a slowing of performance rather than a disruption in accuracy.

The differences in the results of the research reviewed up to this point suggest that the effects of hypercapnia on performance have not been established conclusively.

2.6.7 N_2 Narcosis and CO_2 Narcosis

The main problem with describing the effects of CO_2 and N_2 narcosis on performance is in the classification of how the factors work together. Case and Haldane (1941) postulated that CO_2 potentiates narcosis (Case and Haldane, 1941). Researchers studying the role of O_2 in narcosis suggested that O_2 also acts a potentiator, but believed that it was actually because the high PO2 tensions interfered with the elimination of CO_2

(Frankenhaeuser et al., 1963). The term potentiation implies that a factor modifies narcosis through a common underlying mechanism (Fowler et al., 1985).

In more recent studies, Hesser et al., (1971, 1978) used a mental arithmetic test and a manual dexterity test to measure the effects of excessive $P_{ET}CO_2$ levels on cognitive and psychomotor performance at 70 m (8 ATA). They found that hypercapnia had an additive effect, and the results showed that CO_2 impaired both mental and psychomotor function by approximately 10%. In contrast, the results from the tests conducted at raised ambient pressure, but with normal CO_2 tension, showed a significant 10% decrement in mental function but showed no consistent effect on psychomotor function. Hesser et al. (1971, 1978) were unable to explain the differences in effects, but they concluded that CO_2 and N_2 have different underlying mechanisms.

In a recent study, Fothergill et al. (1989, 1991) demonstrated similar results to those of Hesser et al. (1971, 1978). Fothergill found that there was a significant decrement in performance on all tasks at 50 m (6 ATA); however, cognitive and psychomotor function deteriorated further at $P_{ET}CO_2$ tensions above 47 mmHg. In contrast to the performance decrements noted under conditions of hypercapnia and described above, high P_IN_2 tensions, or N_2 narcosis, caused significant impairment through both decreases in the speed and accuracy of information processing (Fowler et al, 1985; Fothergill 1989; Fothergill et al., 1991). Although Hesser et al. (1971, 1978) didn't offer an explanation for their findings, they arrived at the same conclusion as Fothergill (1989). They both suggested that based on the difference in the effect of CO_2 and N_2 on performance tests, CO_2 and N_2 narcosis have different underlying mechanisms.

There have been other studies on the relationship between N_2 narcosis, CO_2 narcosis and diver performance, but their conclusions vary. A study by Adolfson et al. (1973) demonstrated that body sway was affected by raised $P_{ET}CO_2$ tensions. However, there have been no other studies to support their findings.

Considering the studies to date, the general impression is that the effect of elevated CO_2 partial pressures on cognitive and psychomotor performance at depth is additive (Hesser et al., 1978, 1981; Fowler et al., 1985; Fothergill, 1989; Fothergill et al., 1991). The term potentiation, used in past studies, has been discarded based on the difference in mechanisms noted in recent studies (Hesser et al., 1978; Fothergill, 1989; Fothergill et al., 1991). However, the results that have been documented are not conclusive. All of the above studies were conducted in a dry hyperbaric chamber with subjects breathing compressed air while at rest. To date, there are no known studies that assess the combined effects of underwater exercise, N_2 narcosis and hypercapnia on diver performance under practical diving conditions.

This study aimed to imitate the environment that an open-water working diver would experience during practical diving operations by using an immersion tank in a hyperbaric chamber. Diver performance was assessed in terms of two classifications of skills; psychomotor motor and cognitive. Psychomotor performance was assessed using a battery of reaction time tests including a simple reaction time test and two choice reaction time tests that differed in the level of stimulus-response compatibility. Cognitive performance was assessed using a short term memory test. The tests were performed under conditions of rest and exercise, normocapnia and hypercapnia and immersion, at 0.5 (1 ATA) and 50 m (6 ATA).

Hypotheses

Based on the literature reviewed, it was hypothesized that

1) Sub-maximal exercise in the underwater environment at 0.5 m would facilitate psychomotor performance at low and moderate workloads and prove detrimental at the highest workload, based on the inverted U-hypothesis. In contrast, increasing levels of sub-maximal exercise would not affect cognitive performance.

2) At 50 m N_2 narcosis would produce a decrement in both cognitive and psychomotor performance, under conditions of rest and normocapnia.

3) At 50 m the combined effects of N_2 narcosis and exercise-induced hypercapnia would result in impairment of both psychomotor and cognitive performance. The combined effect of these factors would be significantly greater than the performance impairments caused by N_2 narcosis alone.

3.0 Methods

3.1 Experimental Set-up

Eleven males volunteered to participate in the experiment. In order to participate, an individual had to be a certified PADI or NAUI diver. All interested divers received an information package prior to participating, which explained the research objectives and the experimental procedures. The document was titled *"The risks during exposure to hypo-hyperbaric conditions."* The protocol was reviewed and approved by two independent ethics committees (of the Environmental Physiology Unit and Simon Fraser University), before any experiments took place. Each diver also received a brief description of the hyperbaric chamber and its operation in the *Subject Information Package* as well as a tour of the facility. If there were any questions regarding the procedures and risks involved, they were addressed prior to the subject's giving consent. When the subjects had read and understood the documents, they signed informed consent releases. Subjects were able to withdraw their participation at any time during the experiment.

Subject preparation also involved a medical history questionnaire and a diving medical examination administered by a physician qualified in diving medicine. Subjects were exempt if they had received a diving medical examination within the previous 12 months. All subjects were considered healthy providing they did not have a history of cardiorespiratory disease or any physiological disorders that would prevent a normal response to exercise.

3.1.1 Subjects

Of the eleven subjects that began the study, 10 subjects completed all experimental trials. One subject experienced claustrophobia during a dive and was therefore encouraged to withdraw his participation. Of the remaining 10 subjects, 8 had taken part in hyperbaric chamber dives on previous occasions and the 2 subjects without chamber diving experience were frequent open-water divers. Diver experience ranged from novice to instructor level and diver activity ranged from infrequent (less than once a month) to frequent (more than once a week). Seven of the 10 subjects had participated in studies involving psychomotor or cognitive testing on a previous occasion. All subjects completed a number of practice trials underwater to achieve a learning plateau of performance prior to commencing the experimental trials.

3.1.2 Experimental Location

All experimental sessions took place in the "wet chamber" of the hypo/hyperbaric facility, located in Simon Fraser University's Environmental Physiology Unit (EPU). To familiarize the subjects with the chamber environment, the pre-experimental sessions involved a 15 minute dive to 50 m (165 fsw or 6 ATA).

All experiments took place underwater, with the subject immersed in the prone position in 1.4-1.5 m of water, with a mean lung depth of 0.5 m (as measured between the water surface and the depth of the regulator with the subject positioned in the ergometer and breathing on the regulator). Subjects wore swimming shorts, fins and a diving mask. The mean temperature of the water was 28.3 ± 1.4 C. This temperature was found to be the most comfortable for the resting and exercising phases of the experiment. To minimize bacterial growth, the water was changed weekly and filtered daily, or more often depending on the schedule.

3.1.3 Safety

At all times, a tender was present inside the wet pot of the hyperbaric chamber, alongside the subject. The tender was a certified diver and first aid attendant, and was familiar with the experimental protocol and the operation of the hyperbaric chamber. The physician was also available, within 3 minutes of the EPU, before and during the trials. In case of complications, a crash cart, oxygen tank and emergency medical supplies were located in the EPU.

The hyperbaric chamber was controlled by a qualified chamber operator and an assistant operator. Communication with the tender was provided by a Telex 2400 headset (Helle Engineering). While underwater, the tender and subject received signals via an electronic buzzer with pre-arranged emergency codes as well as codes for the workload and the test battery. The dives were also monitored on a closed circuit television system by the chamber operators and other EPU personnel.

During dives to 50 m, the tender could control the rate of descent as determined by the comfort and safety of both the subject and himself/herself. While on the bottom, the tender was responsible for administering the workload and observing the subject for any signs of distress or severe fatigue. In addition, a backup regulator was available to the subject in case of emergency. The tender was instructed in emergency procedures specific to the hyperbaric wet-chamber.

All dives were followed by the appropriate decompression procedures as determined by the Canadian Forces Air Diving Tables and Procedures (D.C.I.E.M., February 1986 revision). In addition, the subject and tender remained in the EPU for 1 hour so that they could be monitored for signs and symptoms of decompression sickness to ensure that any post-dive incidents likely to occur after the dive could be treated immediately. Both subject and tender wore Medic-Alert bracelets for a 24-hour period following decompression to identify them as divers. The bracelets provided the phone number for Vancouver General Hospital's recompression treatment chamber.

3.2 Apparatus

3.2.1 Ergometer

While immersed, the subject was positioned prone in the shoulder harness of a stainless steel fin-swimming ergometer (refer to Figure 3.1). The ergometer harness was fixed to a carriage that glided on a base fixed to the floor of the chamber. The subject was not restrained in the harness and could disengage simply by pushing backward and standing-up. Forward thrust was maintained against the harness by fin-swimming and weights suspended from the harness provided a reaction force to fin thrust. The weight system consisted of ten 1.1 kg. weights that could be loaded onto a 1.0 kg. hanger.

While underwater, the subject received a warning signal prior to each performance test battery (a single buzz) and prior to an increase in the workload (two buzzes). The warning

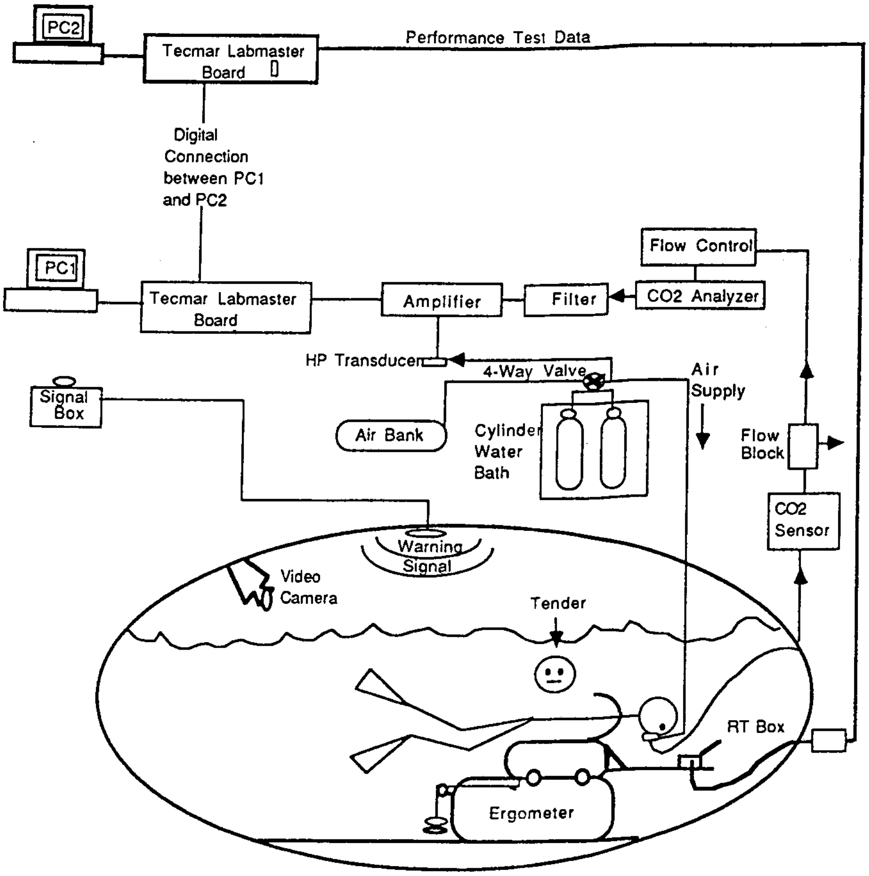

Figure 3.1 Schematic diagram of the equipment and instrumentation used inside the wet-pot and outside the hyperbaric chamber.

signal generator was located outside the chamber while the speaker was located inside the chamber, on the roof of the wet pot. (Figure 3.1)

The underwater component of the reaction time apparatus, the box, rested on a tray attached to the front of the ergometer. The dimensions of the tray provided ample room for the subject to position the reaction time box at an ideal distance for performance. A position feedback indicator was also located in front of the subject, just to the left of the platform. The indicator allowed the subject to maintain the position of the carriage within a set zone to ensure a constant ergometric work rate.

3.2.2. Reaction Time Apparatus

Due to the limitations imposed by experimenting underwater and at hyperbaric pressure, the performance apparatus had to withstand increased pressure and immersion. Many possible performance tests were considered including: traditional "paper and pencil" tests such as arithmetic tests, pattern recognition tests, reasoning tests; manual dexterity tests such as the Purdue Pegboard test, the Bennett Hand Tool Dexterity Test, or tests of valve operation; motor performance tests, such as reaction time tests; and short and long term memory tests. However, the environmental circumstances and the experimental design limited the feasibility of most of the above tests. The experiments were to involve repeated conditions whereby performance would be assessed under each condition, therefore the apparatus should be simple, yet able to assess a variety of different aspects of performance. A reaction time type of system was chosen as the most suitable to the environmental circumstances of the experiment. The design was kept simple, using an open-housing that exposed the components to the environment. The test selection included reaction time tests and a short term memory test. The apparatus is described below, while the rationale for the choice of tests is described in Section 3.3.2.

The stimuli of choice were 4 light emitting diodes (LED). The subject entered a response using 4 simple, white, mechanical push-button switches, as illustrated in Figure

3.2. Due to the nature of the environment, switches were replaced at three week intervals to maintain response integrity. The arrangement of the apparatus was 2.5 cm between the light emitting diodes and 2.75 cm between the switches. The lights were arranged so they were spatially compatible with the response switches. The angle of presentation of the stimulus (LED) surface could be adjusted to the subject's preference using an eye-bolt. Since the apparatus was not attached to the platform, the subject could position it as he chose to.

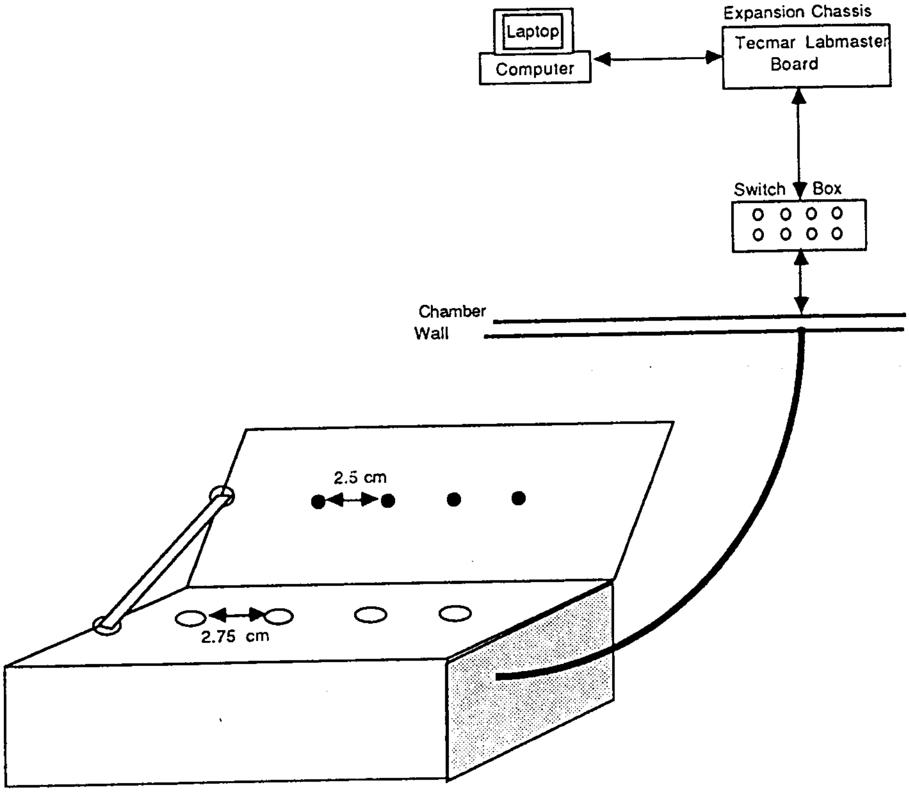

Figure 3.2 Schematic diagram of the apparatus and instrumentation used to assess reaction time and short term memory.

The apparatus was electrically connected through the chamber wall, using a pressure fitting and connected to a switch box outside the chamber (Refer to Figure 3.1). The switch box received both the incoming stimulus signals from the computer and the outgoing response signals from the reaction time box. From the switch box, the signal traveled to an expansion chassis containing a Tecmar Labmaster board, with A to D and digital input/output ports and finally to a Zenith 8086 Laptop computer.

The control program integrated Labmaster Software, for addressing the Labmaster board, into the main routine, which was written in "C". The computer program controlled the onset and offset of the stimulus lights, the status of the switch responses (reaction time) and recorded the number and type of errors. The status of the switches was sampled at 1000 Hz. The over-riding control of the program was through a connection to a second computer, which acted as the master station. The master computer controlled the start of the reaction time program, as well as a warning tone which served to signal the experimenters to change the gas supply line and the tender to change the workload.

3.2.3 Breathing Apparatus

While underwater, the subjects breathed from a single hose, open-circuit demand breathing apparatus. The regulator, a U.S. Divers Conshelf 30, was supplied by one of two cylinders alternatively recharged from the high pressure air bank of the hyperbaric chamber (2700-3000 psi). The breathing gas supply cylinders were switched each minute using a four-way high pressure valve. While one tank was recharging, the charged tank supplied the subject, thus pressure drop could be measured over a one-minute period. A high pressure transducer (Celesco Transducer Prod. Inc., Model PLC, Range 5000 psia) was connected to the outlet of the four-way valve to measure the pressure of the supply cylinder. The linearity of the pressure transducer was tested and found to be within specifications. Throughout the experiment, the cylinders were immersed in a 21 °C water bath to control temperature changes during recharging. A correction factor was also incorporated into the analysis to correct the effect of temperature drop on the measured pressure at the end of a one-minute period. The correction factors were determined by measuring the pressure drop over a one minute interval and then plotting the relationship between the measured changes and the corrected changes following return to ambient pressure (Morrison and Wood, 1986).

To maintain the accuracy of measuring the pressure drop, 2 different tank sizes were used, depending on whether the trial was at 0.5 m (1 ATA) or at 50 m (6 ATA). A 20 cubic foot tank was used for surface trials, while a larger, 80 cubic foot tank was used at depth to provide an adequate air supply at the increased ambient pressure. The 20 cubic foot cylinders supplied air to the first stage at approximately 1500-1800 psi, while the larger cylinders supplied approximately 2000-2300 psi of air to the first stage. The supply pressure to the second stage was set at 140 psi.

3.2.4 Gas Sampling

The mouthpiece of the regulator was a standard rubber mouthpiece except that it had a 3 mm hole drilled into the side of it. A copper tube was then fitted through the hole for sampling end-tidal gas. The tube was 12 cm in length, 2 mm internal diameter and had a 30 degree bend 2 cm from the end. The sampling end of the tube was sealed and a hole was drilled 2 mm from the end so that gas could only enter through the sides of the tube. The tube was placed in the mouthpiece so that the sampling end was directed away from the subject's mouth to prevent saliva or water from entering. The copper sampling tube was connected to tygon tubing that carried the gas sample out of the chamber through a chamber wall pressure fitting.

Unlike gas sampling at surface pressure, at 50 m there is a large pressure effect between the sample source and the sensor outside the chamber. The gas sampling rate at mouth pressure was controlled by selection of narrow gauge sampling tubes which serve to restrict the flow. Gas sampling at 50 m was through a Tygon tube of approximately 0.022 mm internal diameter, while a 1.7 mm tube was used for the 0.5 m experiments.

For the experiments at 50 m, a flow-splitting block was included in the gas sampling arrangement. On exiting the chamber, the gas flow was directed to the CO_2 sensor head and the flow-parting block. The block allowed the excess gas to bleed-off so that gas-flow rates were equal for both surface and pressured experiments. Both the sensor head and the block were located on a platform immediately adjacent to the chamber wall gas sampling penetration. The length of the gas sample tubing, approximately 1.8 m, was minimized by the close proximity of the CO_2 sensor head (Applied Electrochemistry Type P-61B Infrared CO_2 analyzer). The rationale for relocating the sensor head was that the shorter the tube, the less gas mixing that could take place during transport. The response time of the sample line and CO_2 sensor system was measured during the pilot study and was found to be between 200 and 250 msec.

After passing through the sensor head, the sample line was connected to a flowmeter (Applied Eletrochemistry, R-1 Flow control). The flowmeter served to regulate the flow rate between conditions. Flow rate was approximately 400 ml/min for both surface and depth experiments. The above combinations of sample line internal diameter and flow rate provided an acceptable CO_2 signal.

3.2.5 *Signal processing and Computer Interfacing*

The breathing gas pressure and CO_2 signals were filtered at 5 Hz (Rockland Dual Hi/Lo Filter, Model 432), amplified (Daytronic Mainframe, Model 9010, 4-Channel Amplifier) then converted from analog to digital signal (Tecmar Labmaster Board) for computerized sampling and storage (IBM PC 80286). In order to simplify programming, the psychomotor and physiological data were collected using separate computers. The data collection was then synchronized using a digital connection between the two computers. This ensured that the reaction time program started simultaneously with physiological data collection.

The software for data collection was custom designed. The pressure and CO_2 signals were sampled on-line at a frequency of 20 Hz and the data stored on the hard disk. The performance test program sampled the response data on-line at 1 kHz. All data were stored on hard disk and then transferred to diskettes. The psychomotor data were analyzed after each experiment to calculate the mean reaction time for correct responses, the number of error responses and the number of correct responses for the sequence test. The physiological data were also analyzed after each experiment to calculate the mean $P_{ET}CO_2$ and ventilatory parameters for each minute. Statistical analysis of the data took place after all of the experiments were completed.

3.3 Procedure

3.3.1 Pre-experimental sessions

When all subjects had completed their medical examinations and consented that they understood the experimental protocol, they proceeded to the pre-experimental sessions. The first session consisted of three parts while the second session consisted of two parts. Both sessions took place in the order listed below. The subjects had at least a two-day break between sessions.

Session 1	a) introduction to the performance tests
	b) practice performance test session
	c) underwater exercise test at 0.5 m (1 ATA) to determine the workload
Session 2	d) practice performance test session
	e) underwater exercise trial run at 50 m (6 ATA)

3.3.2 Performance tests

The test battery was selected to assess various aspects of performance and included three reaction time tests and one short term memory sequence test. Three reaction time tests were selected to assess the effects of an increased number of stimulus-response alternatives and altered stimulus-response spatial compatibility on reaction time. Reaction time is defined as the time between the onset of the presentation of a stimulus and the depression of the response switch. It is a fundamental component of many skills. It is thought to represent the speed of making decisions and initiating and carrying-out the appropriate actions (Schmidt, 1991). A diver must be alert to his/her environment in order to respond to possible dangers as quickly as possible, therefore reaction time is an important component of actual working divers' tasks.

When measuring reaction time, there is always the possibility that the individual will anticipate the response. To reduce the likelihood of predicting when the stimulus would occur, the total amount of time between trials, made up of the foreperiod and the intertrial interval (ITT), was randomized between 500 and 1500 msec. Figure 3.3A presents the duration of the events for a typical trial. Responses for the first 3 reaction time tests were accepted if the time to react was greater than 150 msec. The mean simple reaction time has been shown to be approximately 190 msec (Hick, 1952) and ranges from 150 and 200 msec (Marteniuk, 1976). A response time less than 150 msec was considered as an anticipatory response. The upper limit for reaction time was 1500 msec which would allow for adequate time for responses during the choice reaction time tests, where the mean reaction time was expected to range from 400-500 msec (Hick, 1952). Response times greater than 1500 msec were considered a "miss". Anticipatory responses and "misses" were not acceptable responses. Subjects were reminded to respond to the stimulus by pressing the appropriate button as quickly as possible. In the case of the simple reaction time test, they were instructed to use their dominant hand in responding to stimuli, while for the choice reaction time tests, they were free to adopt the finger mapping strategy that they found most comfortable.

The fourth test was a sequence short term memory test. A memory test was selected as one of the four performance tests because working divers often recall information relevant to their job and/or to their personal equipment. A short term memory test was chosen to assess the accuracy of recall within a time frame of 10-30 seconds. Figure 3.3B presents the timing sequence for each trial. Each sequence was preceded by a warning period during which all LED's would illuminate for 500 msec and then remain off for 500 msec. After the warning, the sequence began with each LED illuminated for 400 msec, followed by a 400 msec break before the next light in the sequence came on. In total, it took 4400 msec for the complete sequence to be played-out. After the sequence was played, there was a 5000 msec waiting period when all the lights were on which prevented the subject from entering the response. Hence, the minimum time for recall of the first LED was approximately 10 seconds and the maximum time allowed for entering the last LED was 25 seconds. When the lights went off, the subject was able to enter a response. On completion of the response sequence, there was a 2000 msec ITT before the next sequence began.

Due to difficulties in communication between experimenters outside the chamber and subjects inside the chamber, the LED display and switches were used as a means of communication. Before a test could begin, the subject had to signal that he was ready. The pre-test warning signal was provided directly by the computer software. A flashing LED indicated which test was to begin (LED 1, 2, 3, or 4 = test 1, 2, 3, or 4) and cued the subject to get ready. The LED flashed on and off every 500 msec. When the subject felt he was ready to begin, he simply pushed the button below the flashing LED and the appropriate test began.

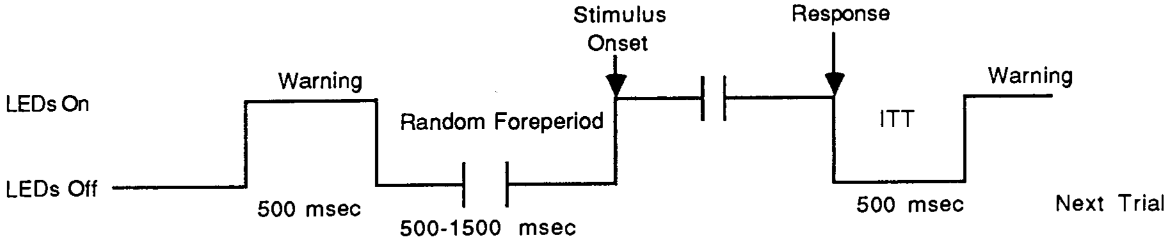

Figure 3.3A Time line of the duration of events for the simple and choice reaction time tests.

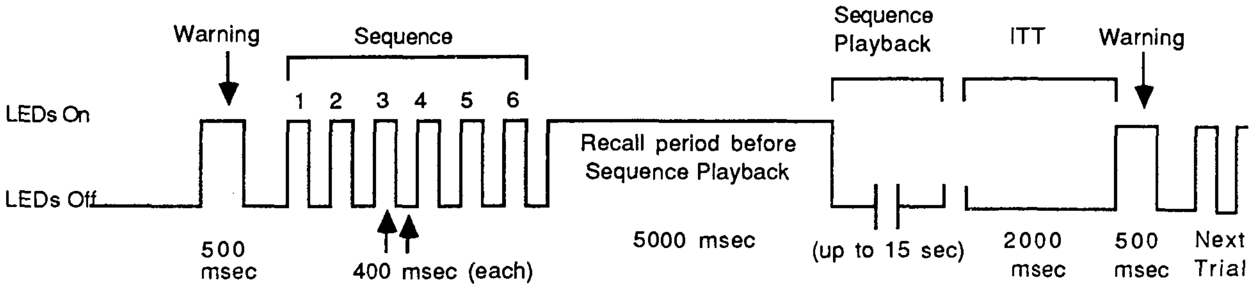

Figure 3.3B Time line of the duration of events for the sequential short term memory test.

Since bottom time is important during hyperbaric exposure, it was essential to provide a time limit for all tests. This was accomplished by limiting the number of trials within each test. The subject was required to complete a number of acceptable responses, that is, responses that were not anticipatory or "misses", within a maximum time. The exception was the short term memory test which involved a set number of sequences and was scored accordingly. The tests are described as follows;

1. Simple reaction time: Defined as the time measured from the onset of the presentation of one stimulus to the depression of the response switch with only one stimulus-response (S-R) alternative. This test required the subject to react as quickly as possible after perceiving the stimulus. The time to respond to the stimulus is believed to be a reflection of the stimulus perception and movement time (Schmidt, 1988). On completion of 10 acceptable responses, the program advanced to the next test. Results included both mean and median reaction time.

2. Choice reaction time (Compatible Stimulus-Response). This test involved four

2. Choice reaction time (Compatible Stimulus-Response). This test involved four possible S-R alternatives. Each of the four LED's was associated with the most spatially compatible response; the button directly below the LED. Hick's Law (1952) describes a linear relationship between reaction time and the number of stimulus-response alternatives, whereby an increase in the number of choices is reflected by an increase in reaction time. The test involved the completion of 20 acceptable responses, whereupon the program advanced to the next test. Results included mean reaction time, median reaction time and number of errors. An error was recorded when the subject made the wrong response to a stimulus provided that the response was within the acceptable time limit.

3. Choice reaction time (Incompatible Stimulus-Response). This test was similar to the test described above with the exception that the compatibility of the S-R alternative was low or incompatible. This was accomplished by organizing the stimulus and response in a spatially dissimilar fashion. In this case, the presentation of a stimulus on the right was associated with an opposite response on the left, so that the four stimuli were associated with four mirrored responses. The information processing of incompatible S-R alternatives has been found to involve additional information processing that is reflected by an increase in reaction time (Fitts and Seeger, 1953). The test involved the completion of 20 acceptable responses, whereupon the program advanced to the next test. Results included mean reaction time, median reaction time and number of errors. An error was recorded when the subject made the wrong response to a stimulus provided that the response was within the acceptable time limit.

4. Short Term Memory. The final test involved a 6-stimulus randomized sequence using four LED's. The light sequence was designed so that there was no immediate repetition of the same LED in the sequence. The subject viewed the sequence, waited 5 seconds, then repeated the sequence using the 4 switches. The test involved 6

such sequences with 2 seconds between each sequence-response set. The subject was given 15 seconds to play back the response before the computer proceeded to the 2 second ITT. The results were recorded as the number of correct responses to the 6 sequences of 6 lights per sequence which gave a maximum score of 36.

3.3.3 Performance Test Practice Sessions

The performance test practice sessions were conducted underwater at rest, while breathing from the regulator and positioned in the ergometer. The purpose of the sessions was to familiarize the subject with the protocol and the environmental setting, with the eventual goal of establishing a plateau of learning performance. Each subject completed two practice sessions, with each session consisting of three sets of the test battery, resulting in six sets. It was found that after six sets of the test battery, the amount of learning between the fifth and sixth set was less than 5% for all tests, that is the reaction time results, number of errors, or scores did not change by more than 5%. The same training protocol was used for all subjects.

In between each test battery there was a 75 second rest break, which was approximately the amount of time between trials during the experiments. The order of presentation of the tests was maintained throughout all trials. In addition, each subject was also required to complete a practice test battery prior to the 0.5 m and 50 m experiments. This resulted in a total of eight practice test batteries being completed by each subject.

3.3.4 Workload Determination

The workload for each subject was determined during the first pre-experimental session, following the first practice test session. The test involved a 12-minute swim on an ergometer at 0.5 m, while breathing from the regulator. Each subject began the swim with a 2.1 or 3.2 kg load, depending on his physical condition and his familiarity with fin-swimming. A 1.1 kg weight was added to the workload by the supervising tender at two minute intervals. Heart rate was recorded throughout the test using a 3-lead, battery-operated electrocardiograph (Fukuda Denshi, FD-13) and used as a means of quantifying the subjects response to the workload. Based on the results of the exercise test, three sub-maximal workloads were selected to represent low, moderate and high exercise levels based on each subject's age-predicted maximal heart rate (HR = 220 - Age). The three workloads allowed the subject to reach approximately 50, 60 and 75% of the age-predicted maximal heart rate.

3.3.5 Pre-experimental exercise trial at 50 m

The second pre-experimental session included a dive to 50 m (6 ATA) following the second practice test session. During the dive, the subject exercised underwater for 5 minutes. The exercise load was incremental, starting with the subject's pre-determined low workload and increasing at a rate of 1.1 kg/min up to the subject's pre-determined high workload. Dive duration was on average 15 minutes and resulted in a total decompression time of approximately 30 minutes.

3.3.6 Experimental Protocol

After the completion of the pre-experimental sessions, the subject proceeded to either the 0.5 or 50 m experiment. There was at least a two-day interval between experiments in order to allow for full recovery from the effects of exercise and decompression. A balanced experimental design was adopted. The dive order was balanced so that half of the subjects did their 0.5 m experiment first, while the other half completed their 50 m experiment first, with the order interspersed over the duration of the study. The experimental protocol was identical for 0.5 and 50 m experiments, except that the 50 m experiments involved 3-5 minutes of compression.

Each experimental session was immediately preceded by a practice test battery with the subject at rest, underwater and breathing from the regulator. During the time in and either rested at 0.5 m or rested while being compressed to 50 m depending on the subject's dive order.

The workload schedule is presented in Figure 3.4. Experiments began with the subject at rest, underwater and breathing from the regulator. There were four conditions; Rest: Low, Moderate and High. Each condition was 5 minutes resulting in a 20 minute experiment, including 5 minutes at rest and 15 minutes of exercise. Near the end of each condition, there was a signal that there would be a change in the workload. The signal consisted of two consecutive buzzes from a device within the chamber that could be easily heard underwater. The signal came 10 seconds before the end of the fifth minute of each condition and served to warn both the subject and the tender of the increase in the workload. The tender was responsible for administering the workload and for monitoring the status of the subject.

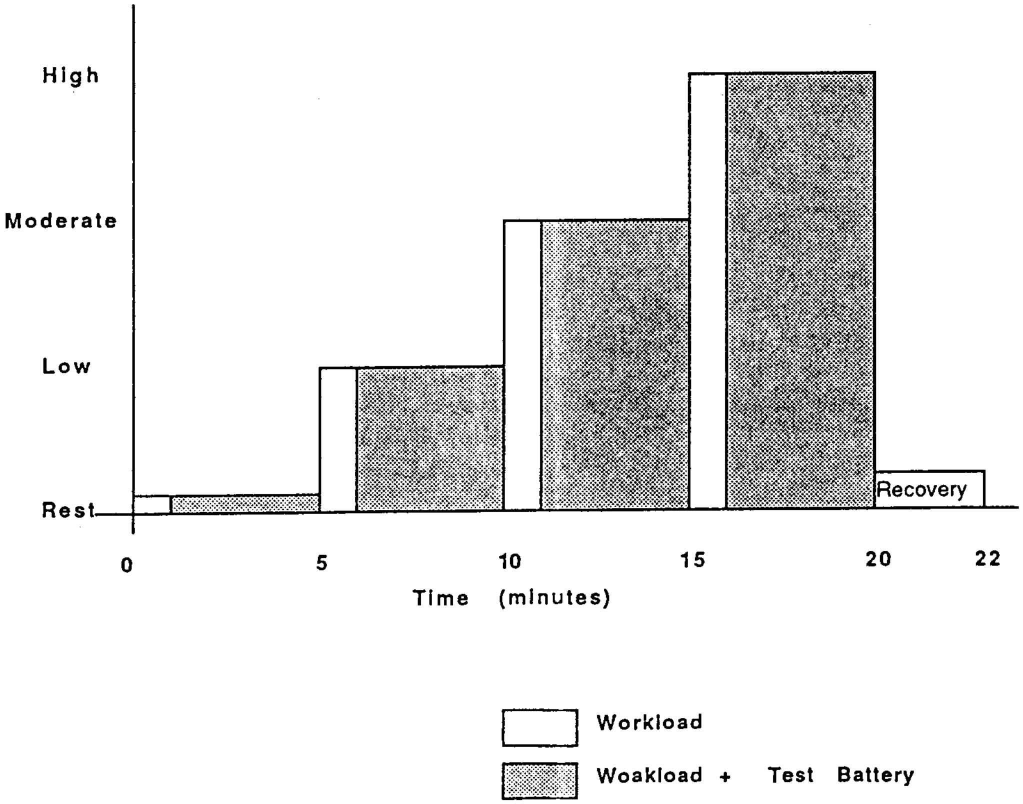

Figure 3.4 Workload and test battery schedule for the 0.5 and 50 m experiments.

The first minute of each of the four conditions allowed the subject to adapt to the workload. Ten seconds before the end of the first minute, the subject received a signal (single buzz) that warned him that the test battery was to begin. The order of the tests was maintained throughout the conditions, and is listed on the next page.

1. simple reaction time;
2. 4-choice reaction time with compatible S-R alternatives;
3. 4-choice reaction time with incompatible S-R alternatives;
4. 6-sequence short term memory.

Although the duration of each of the four performance tests varied, all four tests could be completed within the 4 minutes allotted for performance testing during each condition. During the pilot study, it was found that most subjects had at least a 15 second break on completion of the fourth test, before commencing the next workload, resulting in a 75 second break between the test batteries. Once the protocol was completed at rest, it was repeated during the subsequent three exercise conditions. At the completion of the 20 minute experiment, the subject was allowed to rest for a approximately 2 minutes prior to decompression procedures. All dives were followed by the appropriate decompression schedule. The maximum duration of all dives was 30 minutes, resulting in one hour, 30 minutes of decompression on air. The second experiment with the same subject was conducted at least 2 days after the first experiment.

3.4 Data Collection and Analysis

3.4.1 Physiological Data

The end-tidal and inspired carbon dioxide fractions were determined using breath-by-breath analysis over the first 45 seconds of each minute. Mean end-tidal partial pressure of carbon dioxide ($P_{ET}CO_2$) was then calculated by averaging the maximum breath-by-breath values, or the peaks, from the 45 seconds of data, applying the formula below (1),

$$P_{ET}CO_2 = F_{ET}CO_2 \text{ X } [\, P_A / (P_A - P_{H2O}) \,] (P_A + P_D - 47.1) \qquad (1)$$

where: $F_{ET}CO_2$ = mean end-tidal fraction of carbon dioxide

P_A = barometric pressure (mmHg)

P_D = ambient pressure at the dive depth, including the hydrostatic load on the subject's regulator (mmHg)

P_{H2O} = water vapour pressure of gas sample at ambient temperature (mmHg).

The inspired partial pressure of carbon dioxide (P_ICO_2) was calculated using the formula described above except that the minimum breath-by-breath values (troughs) were selected.

Gas ventilation by the subject was determined first based on the time-corrected pressure drop over each minute and expressed as dry gas volumes under standard pressure (VI_{SP}) at 0.5 m. The high pressure air supply data were analyzed to determine the peak to peak pressure drop over the sampling period. The pressure data were corrected for isothermal expansion, using a formula determined experimentally by Wood and Morrison (1986). Minute ventilation was then calculated using the known cylinder volumes, the temperature corrected pressure drop over the minute and the following formula, resulting in ventilation corrected for body temperature and pressure saturated conditions (VI_{BTPS}).

$$VI_{BTPS} = VI_{SP} \text{ X } [\, 760 / (P_D + P_A - 47.1) \,] \text{ X } [\, 310 / 273 + T_b \,] \quad (2)$$

Where; P_D = ambient pressure at the dive depth, including the hydrostatic load on the subject's regulator (mmHg).

P_A = barometric pressure (mmHg).

T_b = temperature of the cylinder water bath (°C).

Breathing frequency (B_f min^{-1}) was determined by analyzing the breath-by-breath $CO2$ peaks over the sampling period. Tidal volume (V_T), or the volume of each breath was calculated by dividing minute ventilation (VI_{BTPS}) by the breathing frequency (B_f).

All variables were averaged over each minute, with the results from the last four minutes of each workload used to determine the mean for each condition. Data from the first minute of each workload were not included in the analysis since the subject was not engaged in the test battery during that time.

3.4.2 Performance Data

The first step in the analysis of the reaction time data was to determine whether the time to respond was acceptable; that is, whether it was greater than the minimum reaction time (150 msec) and less than the maximum time permitted (1500 msec). Once the unacceptable responses were discounted, the remaining data were analyzed to determine whether the response was correct. A mismatch between the stimulus and response code resulted in an error. Error scores were recorded for both of the choice reaction time tests. There was no error score for the simple reaction time test because there was only one possible stimulus-response combination. The results of the reaction time tests were calculated based on the acceptable responses and the timed results were reported in terms of the mean and the median reaction time (msec).

The data from the sequence memory test were analyzed by comparing each six light sequence entered with the correct six light sequence, over all six sequences. The result was a score out of 36 for each test.

The results of the performance tests were expressed in two forms: time, error (reaction time tests) or score (memory test); and as a performance decrement. The data was expressed as a performance decrement for two reasons: first, it allowed for the comparison of the results with the literature; and second, it allowed for comparison of the magnitude of the change in performance across the tests.

The formula for calculating the performance decrement is expressed below (3). The performance decrement represents the difference between the group mean for the control conditions (GMControl) (rest at 0.5 m) and the group mean for the various experimental conditions (GMExperimental). Performance decrements were expressed as a percentage.

$$\text{Decrement} = [\,(\text{GMControl} - \text{GMExperimental}) / \text{GMControl}\,] \times 100 \quad (3)$$

3.4.3 Statistical Analysis

The experimental data fall into two broad categories of dependent variables: physiological and performance. The physiological variables are $P_{ET}CO_2$, V_I, V_t and B_f. The performance variables are the simple reaction time test (SRT), the compatible and incompatible choice reaction time tests (cCRT and iCRT, respectively) and the memory sequence test (Mem).

The overall design of the study was based on groups that were balanced such that half of the subjects did the 0.5 m experiment first while the other half did the 50 m experiment first. In addition, in all cases, the order of the conditions was rest, low, moderate and high workloads and the order of the tests was SRT, cCRT, iCRT and MEM. The data were first analyzed to determine whether balancing the groups between the 0.5 and 50 m depth order had an effect on the performance test results. Following the outcome of the order or group analysis, the next step was to analyze the effects of the independent factors (or main effects) on the performance data. The hypotheses involved three effects: underwater exercise, N_2 narcosis (P_IN_2) and the combined effect of nitrogen narcosis, exercise and exercise-induced hypercapnia.

The order of the workloads progressed from rest through three incremental levels of exercise. Clearly the order could not be randomized due to the physiological after-effects of exercise, therefore there is the possibility of an order effect in the data. If the order of workload had an effect on the performance test results, it would contribute to a possible exercise effect on performance; however, the two effects could not be separated. Hence, if a significant exercise effect was found, it would be attributed to both the order of the workloads on performance and the effect of exercise on performance.

The reaction time data were first analyzed to examine the effects of the number of S-R alternatives (set size) and S-R compatibility on reaction time and error frequency, for each of the hypotheses. The effect of set size was determined using the SRT and cCRT data while the effect of stimulus-response compatibility was analyzed using the cCRT and iCRT data. The short term memory data were analyzed independently of the reaction time data.

The N_2 narcosis effect was determined using a two-way ANOVA to compare the results for each of the tests under resting conditions, with repeated measures across the two levels of inspired nitrogen partial pressure and the test(s). A similar approach was applied to analyze the effect of increasing levels of exercise at 0.5 m on performance. A two-way ANOVA was used with repeated measures across the four workloads and the test(s). The combined effect of pressure and workload on performance was analyzed using a three-way ANOVA, with repeated measures across all factors.

If the analysis of the main effects yielded significant F statistics, *post hoc* multiple comparisons were performed using Tukey's HSD to identify the level or levels within the factors where the significant differences in means occurred. Any interaction effects between the factors, as indicated by significant F statistics, would be identified using Scheffe's post-hoc test for interactions. The *a priori* significance was set at the 0.05 level for all statistical tests except when Scheffe's test for *post hoc* interactions was used. When a significant interaction effect was observed, *post hoc* analysis was performed using Scheffe's test with the *a priori* significance set at the 0.1 level due to the conservative nature of the test (Shavelson, 1988).

The results for each of the tests were expressed in terms of a percentage change relative to the mean control results at 0.5 m under rest conditions. The data represented the decrement in performance for each of the conditions. If ANOVA revealed that the main effect for a test was not significant, then the performance decrement results were collapsed across all tests for further analysis. The final step involved regression analysis on the performance decrement data. The rationale behind regression analysis was to produce a model for describing the performance decrement as a function of the diving conditions. The independent factors included in the analysis were workload, test, P_IN_2 and $P_{ET}CO_2$. The reason for using regression analysis was to examine the relationship between the independent factors and the performance data.

4.0 Results

4.1 Subject Characteristics

The physical characteristics of the subjects are listed in Table 4.1. The mean age of the subjects was 30.1 ± 8.6 years. The mean height and weight of the subjects were 1.8 ± 0.07 m and 74.1 ± 6.7 kg, respectively. Table 4.1 also classifies the divers based on how often they dive. Three levels of diving activity are defined below. All subjects were certified divers with a minimum qualification of Level 1 (open water dive) under either PADI or NAUI regulations.

The subjective reports by the divers included a few incidents of mild frontal headaches following the 50 m experiments, where the $P_{ET}CO_2$ levels were highest. In addition, some participants reported muscle soreness a day or two after an experiment. The majority of subjects reported overall fatigue after the 50 m experiments.

Table 4.1: Physical characteristics of the subjects (n = 10).

Subject	Age (yrs)	Weight (kg)	Height (m)	Diving Activity
1	23	70.5	1.73	M
2	24	70.5	1.80	M
3	47	77.5	1.83	M
4	31	73.5	1.78	I
5	24	75.4	1.83	M
6	23	63.6	1.85	I
7	26	70.5	1.68	I
8	37	70.0	1.75	M
9	41	85.0	1.80	F
10	25	84.1	1.91	F
Mean	30.1	74.1	1.80	-
S.E.M.	8.6	6.7	0.07	-

F : frequent (more than once per week)
M : moderate (more than once per month)
I : infrequent (less than once per month).

4.2 Physiological Data

Table 4.2 lists the mean (n=10) and standard error of the mean (S.E.M.) for the various physiological variables. The ventilation results are expressed under conditions of body temperature and pressure saturated air (BTPS). The results are presented at the four workloads; Rest, Low, Moderate and High and at two hyperbaric pressures; 0.5 m (1 ATA) and 50 m (6 ATA).

Overall, the mean $P_{ET}CO_2$ results were significantly higher at 50 m than at 0.5 m, when all workloads were considered together (F=65.71, df=1,9, $p<0.001$). Furthermore, the presence of a significant interaction effect indicated that $P_{ET}CO_2$ changed with the change in workloads (F=34.29, df=3,27, $p<0.001$). The change was not significant at 0.5 m (df=3,9 f=1.92, $p=0.144$); however, the change was significant at 50 m (F=20.95, df=3,27, $p<0.001$). *Post hoc* analysis indicated that the $P_{ET}CO_2$ levels measured at the moderate and highest workloads at 50 m were significantly higher ($p<0.05$) than all levels recorded at 0.5 m, and higher than the resting $P_{ET}CO_2$ at 50 m. However, a significant difference was not identified between the 0.5 and 50 m $P_{ET}CO_2$ levels measured at rest or at the low workload.

Table 4.2: Group mean and standard error of the mean for respiratory responses measured at rest and three levels of exercise, at 0.5 and 50 m (n = 10).

Variable	**0.5 m (1 ATA)**				**50 m (6 ATA)**			
(S.E.M.)	**Rest**	**Low**	**Moderate**	**High**	**Rest**	**Low**	**Moderate**	**High**
$P_{ET}CO_2$	42.27	45.51	46.82	47.09	49.74	55.61	60.58	65.15
[mmHg]	(0.94)	(1.39)	(1.74)	(2.09)	(1.72)	(2.16)	(3.12)	(3.14)
V_i	14.58	23.07	32.85	48.43	17.25	23.76	32.42	42.80
[l/min]	(0.71)	(1.06)	(2.20)	(2.57)	(1.12)	(1.42)	(1.90)	(2.06)
V_t	1.9	2.6	2.8	3.0	2.4	2.7	2.8	2.8
[l]	(0.14)	(0.19)	(0.13)	(0.18)	(0.32)	(0.23)	(0.23)	(0.22)
B_f	8.1	9.4	12.2	16.5	8.4	9.4	12.5	16.6
[br/min]	(0.7)	(0.7)	(0.9)	(1.4)	(1.0)	(0.8)	(1.3)	(1.6)
HR	70	93	112	140	69	88	104	127
[bpm]	(3.5)	(4.1)	(4.2)	(4.1)	(3.2)	(2.8)	(4.1)	(5.2)

The highest mean $P_{ET}CO_2$ value recorded was 65.15 mmHg at the highest workload at 50 m. The maximum individual $P_{ET}CO_2$ was 83.2 mmHg, recorded while a subject was exercising under the same conditions.

As the level of hypercapnia increased, so too did the measured minute ventilation (F=203, df=3,27, $p<0.001$), however the ventilatory response to CO_2 differed for the two depths. (Figure 4.1). When the ventilatory data were studied independently of $P_{ET}CO_2$, the ventilation rate at rest was greater during the experiments at 50 m, while at the highest workload, the ventilation rate was greater during the experiments at 0.5 m (F=5.14, df=3,27, $p<0.05$).

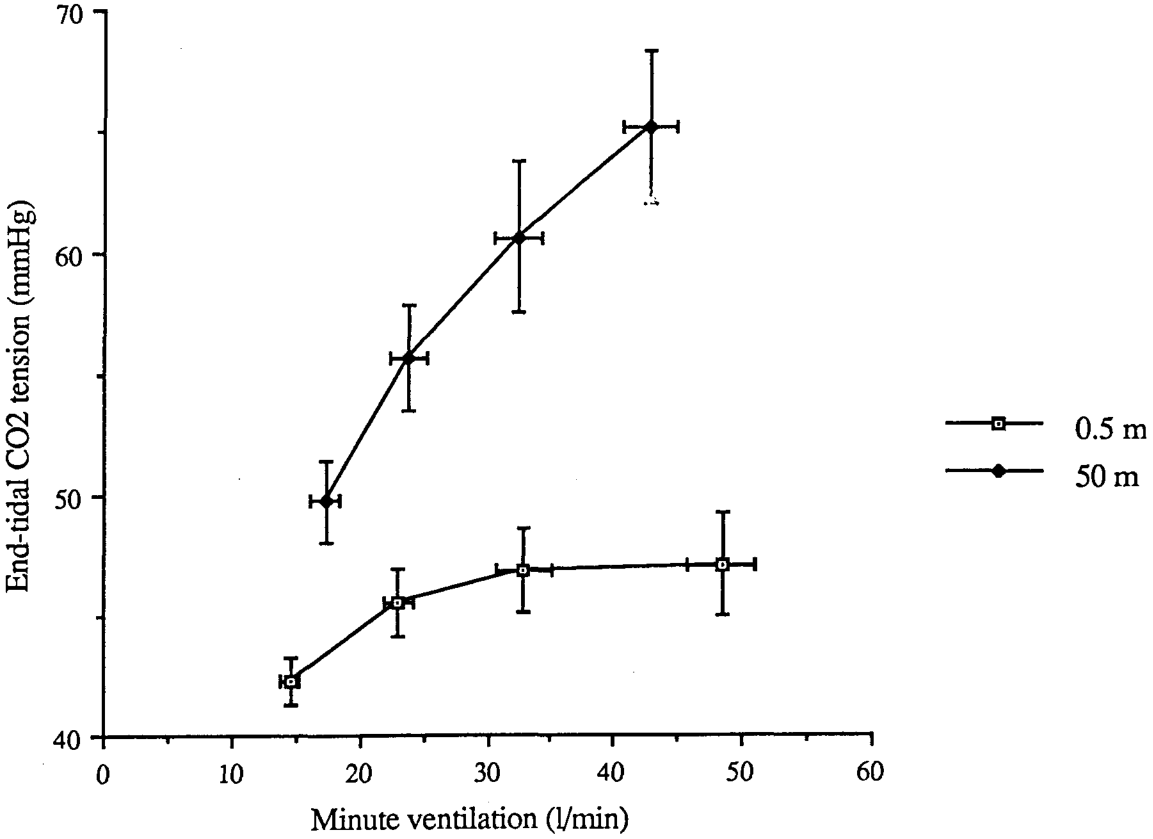

Figure 4.1 End-tidal CO_2 versus Minute Ventilation for all conditions at 0.5 and 50 m (values are means, bars are S.E.M.).

The increase in ventilation across the levels of exercise reflected the combination of an increase in tidal volume (F=25.73, df=3,27, $P<0.001$) and breathing frequency (F=67.65, df=3,27, $P<0.001$). Overall, the tidal volume increased significantly more during the experiments at 0.5 m, as indicated by the significant interaction effect (F=5.6, df=3,27, $p<0.05$). Breathing frequency, however, showed the same increase for both the 0.5 and 50 m experiments.

Heart rate reflects the physical demands of aerobic exercise; therefore, it follows that as the level of exercise increases, the heart rate is expected to increase. There was a significant increase in heart rate for both the 0.5 and 50 m experiments (F=97.88, df=3,27, $P<0.001$), with a larger increase observed during the 0.5 m experiments than at 50 m (F=7.06, df=3,27, $P<0.05$). At rest, the mean heart rate was 70 bpm at both depths, which indicates that depth-related bradycardia was not present. However as the workload increased, depth-related bradycardia became evident with mean heart rates of 140 and 127 at the highest workloads, for the 0.5 and 50 m experiments, respectively.

4.3 Performance Test Data

4.3.1 Preliminary test-retest results

For all three of the reaction time tests, the subjects achieved a complete number of acceptable responses, as outlined in section 3.3.2. Table 4.3 lists the mean and the standard error of the mean (S.E.M.) of the practice sets performed prior to the 0.5 m (1 ATA) and 50 m (6 ATA) experiments.

Table 4.3: Mean pre-experimental practice results for the 0.5 and 50 m experiments and pairwise comparisons for the test battery (n=10). Results are expressed in terms of reaction time (msec), number of errors, or percentage correct (memory test).

Performance Test	0.5 m	(S.E.M)	50 m	(S.E.M)	p-value
SRT (msec)	253.8	(10.7)	238.0	(10.7)	0.164
cCRT (msec)	339.7	(7.9)	330.7	(8.1)	0.457
errors (#)	1.1	(0.46)	0.6	(0.30)	0.475
iCRT (msec)	394.0	(11.5)	394.7	(12.4)	0.944
errors (#)	1.1	(0.54)	0.6	(0.26)	0.464
Mem (%)	95.3	(2.3)	96.9	(2.3)	0.266

The results of pairwise comparisons are listed in the right-hand column of Table 4.3. The p-values from the comparisons are non-significant and range from 0.164 to 0.944. The probability levels indicate that there was no significant differences in reaction time, number of errors, or score, between the two testing occasions, prior to the 0.5 and 50 m experiments.

4.3.2 Experimental performance test results

Since the overall design of the study was based on groups that were balanced, rather than randomized, the data were first analyzed to determine whether an order effect was present on the performance test results. One group of subjects ($n = 5$) progressed from the 0.5 to the 50 m experiments, while the other group ($n = 5$) underwent the experiments in the reverse order; 50 m to 0.5 m. The analysis did not identify an order effect ($F = 0.00$, $df = 1$, $p = .949$) therefore the data were collapsed across the groups for analysis of the effects of exercise, N2 narcosis and the combined effect. The results are presented below in Table 4.4.

For the three reaction time tests, both the mean and the median reaction times were determined. Table 4.4 presents the results for mean reaction time. It was found that although median reaction time was consistently lower than mean reaction time, suggesting a slight positive skew to the data, the difference was small. Furthermore, the mean and median reaction time data followed similar trends across the conditions.

The effect of increasing levels of concomitant exercise on performance was analyzed using the data from the resting condition and the three workloads at 0.5 m. The rationale for using the 0.5 m data was that the expected change in $P_{ET}CO_2$ tensions would be negligible under normobaric conditions, therefore any effects on performance would be attributed to exercise. *Post hoc* analysis of the 1 ATA $P_{ET}CO_2$ data indicated that the increase in $P_{ET}CO_2$ with workload was not significant ($F = 1.92$, $df = 3$, $p = 0.144$).

Table 4.4: Performance results for the test battery of four tests for all experimental conditions. Results for the reaction time tests are expressed in terms of mean reaction time (msec) and number of errors. Results for the memory test are expressed as a score.

Performance		0.5 m	(1 ATA)			50 m	(6 ATA)	
Test	Rest	Low	Moderate	High	Rest	Low	Moderate	High
SRT	262.4	262.6	278.9	276.9	269.8	285.1	284.0	319.6
(S.E.M.)	(7.7)	(13.7)	(14.9)	(19.7)	(14.5)	(13.5)	(13.9)	(25.5)
cCRT	342.6	351.0	358.2	349.6	368.3	362.3	382.9	425.9
(S.E.M.)	(9.0)	(13.3)	(9.8)	(10.7)	(11.3)	(9.3)	(12.1)	(21.0)
errors	0.5	0.8	1.0	0.6	0.5	0.6	0.9	1.0
(S.E.M.)	(0.2)	(0.3)	(0.3)	(0.4)	(0.2)	(0.3)	(0.4)	(0.5)
iCRT	403.4	411.3	392.5	393.9	436.0	418.4	439.8	476.8
(S.E.M.)	(9.7)	(13.2)	(6.9)	(15.9)	(21.4)	(11.4)	(17.9)	(24.0)
errors	1.0	1.1	0.6	1.1	1.6	1.0	1.5	1.4
(S.E.M.)	(0.3)	(0.5)	(0.3)	(0.4)	(0.3)	(0.3)	(0.4)	(0.5)
Mem	96.1	94.8	93.0	87.1	89.5	80.9	81.9	67.4
(S.E.M.)	(1.1)	(2.1)	(3.0)	(5.9)	(3.0)	(3.8)	(5.1)	(7.0)

The effect of an increase in $P_{I}N_{2}$ was analyzed using the data from the resting condition at 0.5 m and 50 m, where the $P_{I}N_{2}$ was 0.79 ATA and 4.8 ATA. The rationale for using the resting data was that under resting conditions the N_{2} effect could be isolated without any expected difference in $P_{ET}CO_{2}$ tensions. However, the $P_{ET}CO_{2}$ levels measured during the resting conditions at 0.5 and 50 m were approximately 42 and 49 mmHg, respectively. Although *post hoc* analysis did not identify a significant difference between the two levels, the difference appears large enough to have possibly corrupted the N_{2} effect.

Analysis of the performance data for all of the conditions together provided the results for the combined effects of underwater exercise, N_{2} narcosis and exercise-induced hypercapnia on performance.

4.3.2.1 Reaction Time Tests

The results of the reaction time tests are displayed in Figures 4.2 (A, B, C) and 4.3 (A, B, C). Figures 4.2 present mean reaction time as a function of the number of stimulus-response alternatives (set size), while Figures 4.3 present the reaction time data as a function of stimulus-response (S-R) compatibility for each of the effects, exercise (A), N_2 (B) and combined (C). The section on S-R compatibility also describes the effects of exercise, N_2 and combined, on the number of errors made during the choice reaction time tests.

Set Size

Figures 4.2 A, B and C display the relationship between mean reaction time and set size for the effects of exercise, N_2 and combined effects. In all cases, reaction times were significantly higher when the number of stimulus-response alternatives was four (cCRT) than when only one S-R alternative was presented (SRT). This was supported by statistical analysis which indicated that the main effect for set size was significant across workloads ($F=47.34$, $df=1,9$, $p<.001$), between N_2 levels ($F=48.26$, $df=1,9$, $p<.001$) and when the effects of pressure and workload were combined ($F=40.11$, $df=1,9$, $p<.001$).

There was no significant change in reaction time with increasing levels of exercise (Fig. 4.2A) or N_2 (Fig. 4.2B), hence neither exercise nor N_2 had an identifiable effect on reaction time as assessed as a function of set size.

When workload and pressure were combined (Fig. 4.2C), the effect was a significant increase in reaction time across workloads ($F=9.58$, $df=3,27$, $p<.001$) and between N_2 levels ($F=5.17$, $df=1,9$, $p<.05$), in addition to a significant interaction effect ($F=4.11$, $df=3,27$, $p<.05$). The presence of the interaction effect alters the interpretation of the main effects. The observed change in reaction time varied across the levels of exercise and between depths, with the longest reaction times observed at the highest workload at 50 m for both tests.

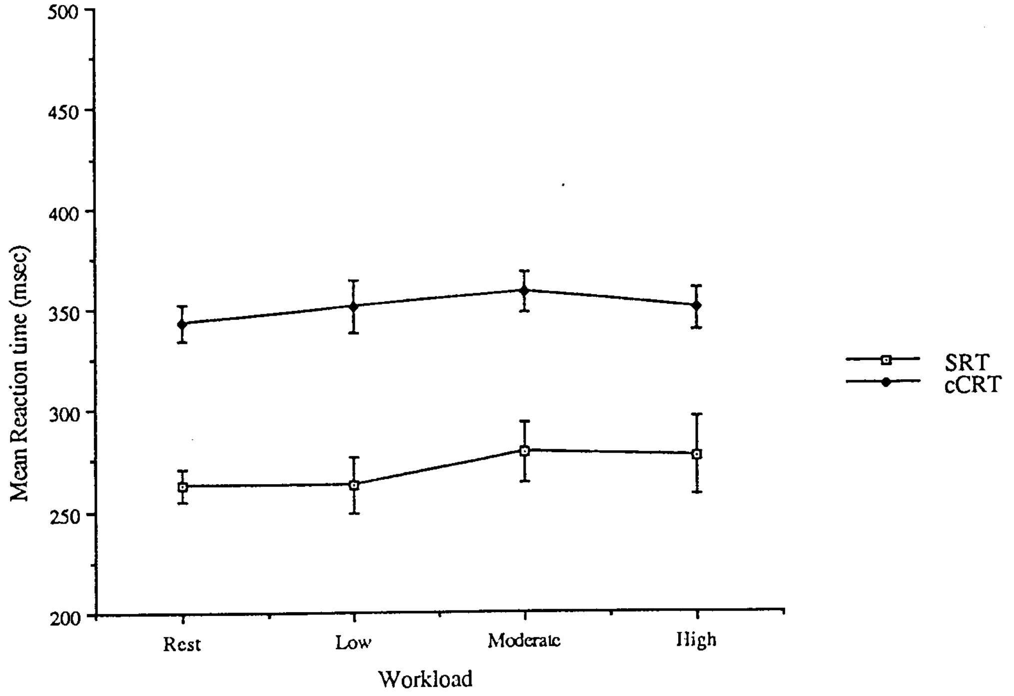

Figure 4.2A Exercise effect on reaction time as a function of set size (values are mean, bars are S.E.M.).

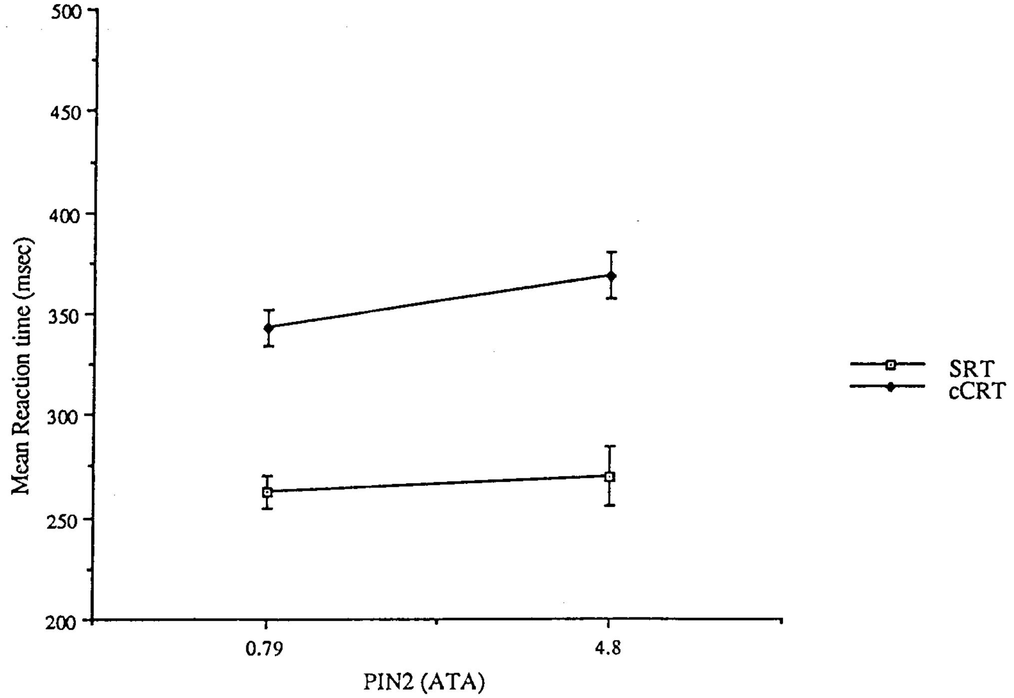

Figure 4.2B Nitrogen narcosis effect on reaction time as a function of set size (values are mean, bars are S.E.M.).

Post hoc analysis of the combined effect revealed that choice reaction time at the highest workload at 50 m was significantly higher than at all workloads at 0.5 m and at the light workload at 50. Simple reaction time did not show any significant change with an increase in workload at either pressure.

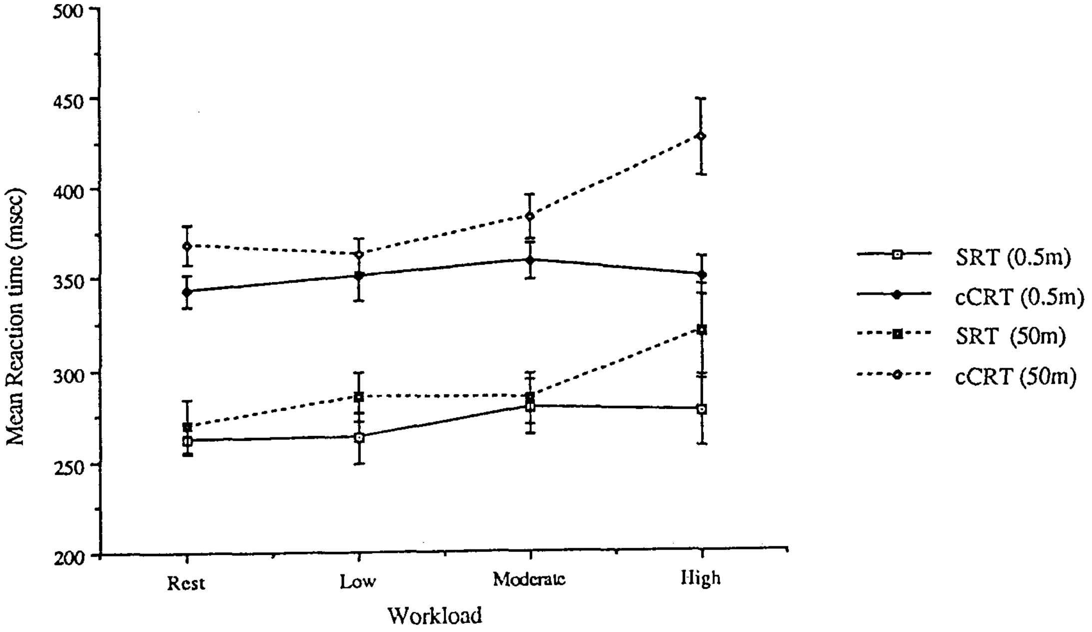

Figure 4.2C Combined effects of exercise, N_2 narcosis and exercise-induced hypercapnia on reaction time as a function of set size (values are mean, bars are S.E.M.).

Stimulus-Response Compatibility

The relationship between S-R compatibility and reaction time is displayed for each of the effects (Figures 4.3 A, B and C). In all cases, reaction times were significantly longer when S-R compatibility was low, indicating that the main effect for compatibility was significant across the workloads at 0.5 m (F=45.37, df=1,9, $p<.001$), between N_2 levels (F=34.57, df=1,9, $p<.001$) and when the effects of workload and pressure were combined (F=41.80, df=1,9, $p<.001$).

Increasing levels of exercise did not significantly affect choice reaction time (Fig. 4.3A), however, there was a significant increase in reaction time with the increase in P_IN_2

(F=6.55, df=1,9, p<.05). The N_2 effect was evident for both tests with significantly longer reaction times when the P_IN_2 was 4.8 ATA, as displayed in Figure 4.3B,.

Figure 4.3C displays the combined effects of pressure and workload on choice reaction time as a function of S-R compatibility. When pressure and workload were combined the main effects were significant however, there was also a significant interaction effect (F=7.95, df=3,27, p<.001). The presence of an interaction indicates that the change in reaction time varied across the workloads and between the two pressures. The longest reaction times were measured when the subject was exercising at the highest workload at 50 m, as shown in Figure 4.3C.

Post hoc analysis revealed that reaction time at the highest workload at 50 m was significantly greater than at the moderate and highest workloads at 0.5 m for the incompatible choice reaction time test. The results of the post hoc analysis on the compatible reaction time test are described previously.

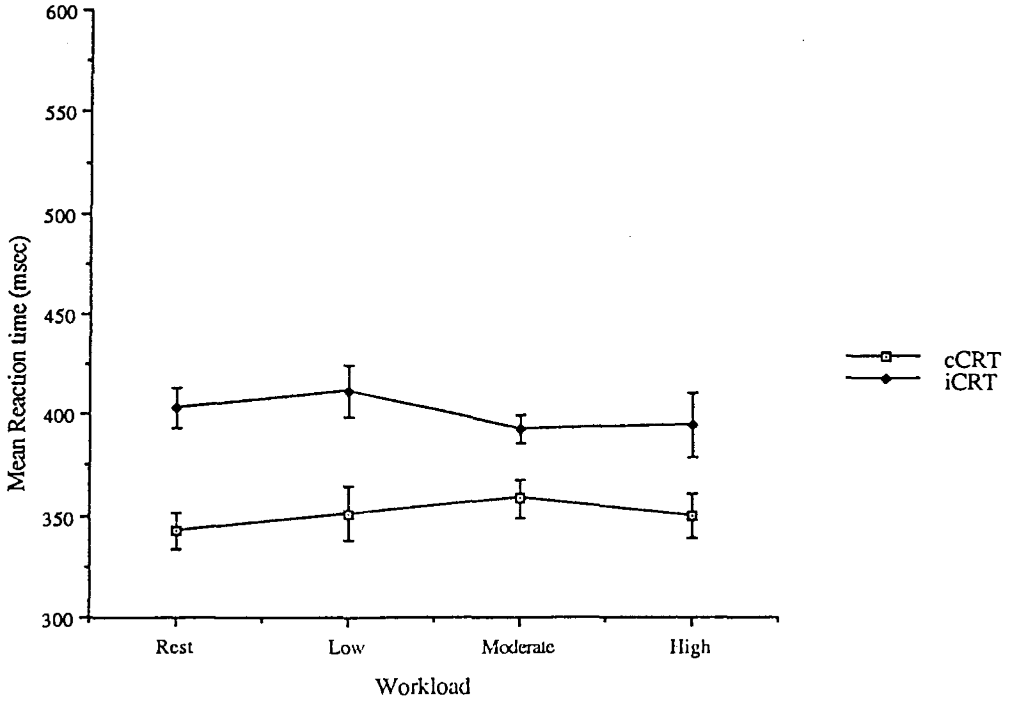

Figure 4.3A Exercise effect on reaction time as a function of S-R compatibility (values are mean, bars are S.E.M.).

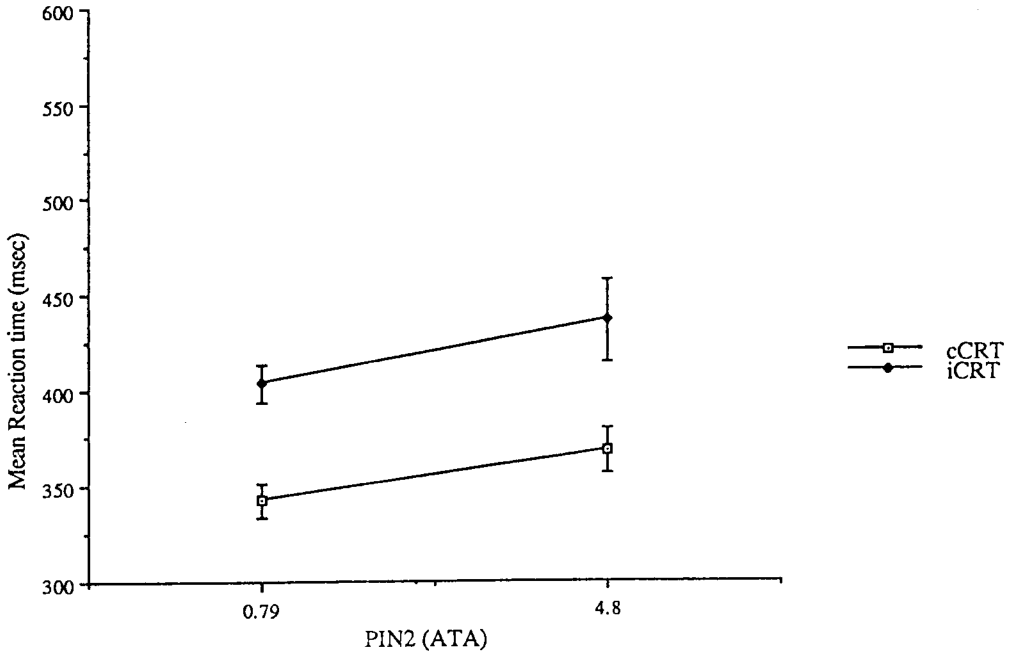

Figure 4.3B Nitrogen narcosis effect on reaction time as a function of S-R compatibility (values are mean, bars are S.E.M.).

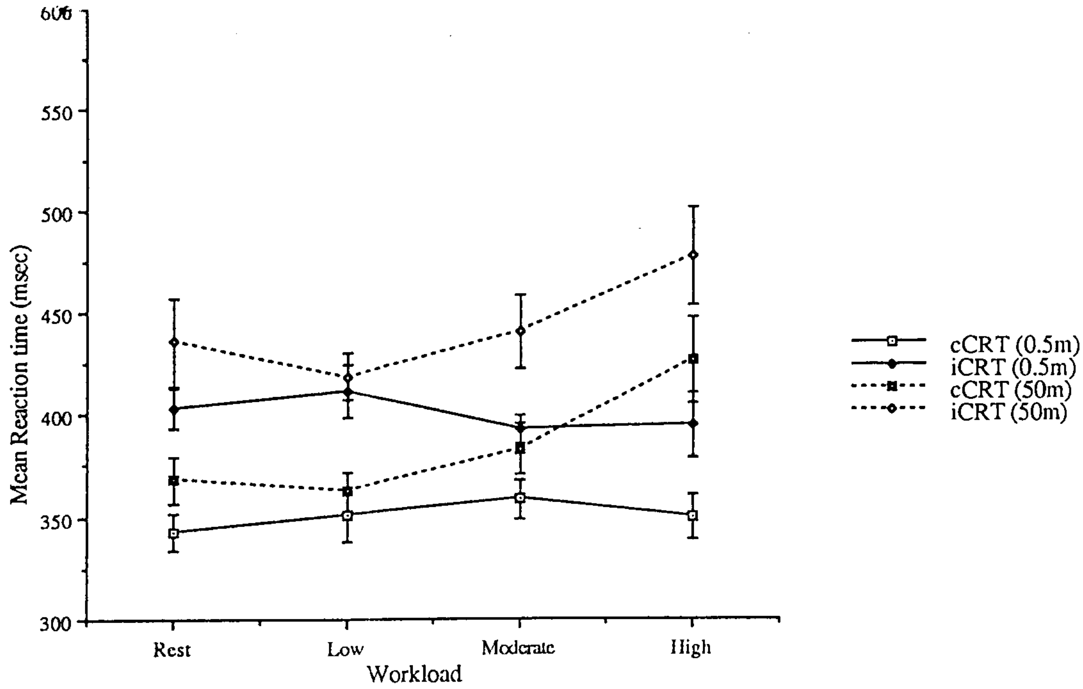

Figure 4.3C Combined effects of exercise, N_2 Narcosis and exercise-induced hypercapnia on reaction time as a function of S-R compatibility (values are mean, bars are S.E.M.).

Error frequency

Data representing the number of errors made during the choice reaction time tests (cCRT and iCRT) are presented in Table 4.4. Analysis of variance revealed that increasing the level of exercise at 0.5 m had no significant exercise effect on error frequency, with both choice reaction time tests showing the same response. An increase in the level of P_IN_2 also showed no significant effect on the number of error made; however, the data revealed that at both levels of P_IN_2, significantly more errors were made on iCRT than on cCRT ($F=16.0$, $df=1,9$, $p<.005$). Finally, there was no evidence of an increase in error frequency with the combined effects of increased pressure and/or workload for either tests.

4.3.2.2 Short Term Memory Test

Figures 4.4 A, B and C display the results for the 6-sequence memory test for each of the effects exercise (A), nitrogen (B) and combined (C). The results are presented as the percentage correct, with 100% representing a perfect score of 36 out of 36.

An exercise effect was not identified (Figure 4.4A), in that an increase in the workload did not significantly affect the subjects' ability to recall the sequences. However, the percentage correct did change significantly with an increase in the P_IN_2 ($F=6.05$, $df = 1,9$, $p < .05$), indicating that a N_2 effect was identified (Figure 4.4B). The mean percentage correct at 50 m (89.5%) was significantly less than that at 0.5 m (96.1%).

When the combined effect of workload and pressure was analyzed, both main effects were significant (Figure 4.4C). Since there was no significant interaction between pressure and workload the main effects can be interpreted individually. The presence of a significant pressure effect ($F=13.44$, $df=1,9$, $p=.005$) indicates that the percentage of sequences recalled correctly was significantly less at 50 m as compared to 0.5 m, when all workloads were considered together. The mean score at 0.5 m was 93% compared to 80% at 50 m.

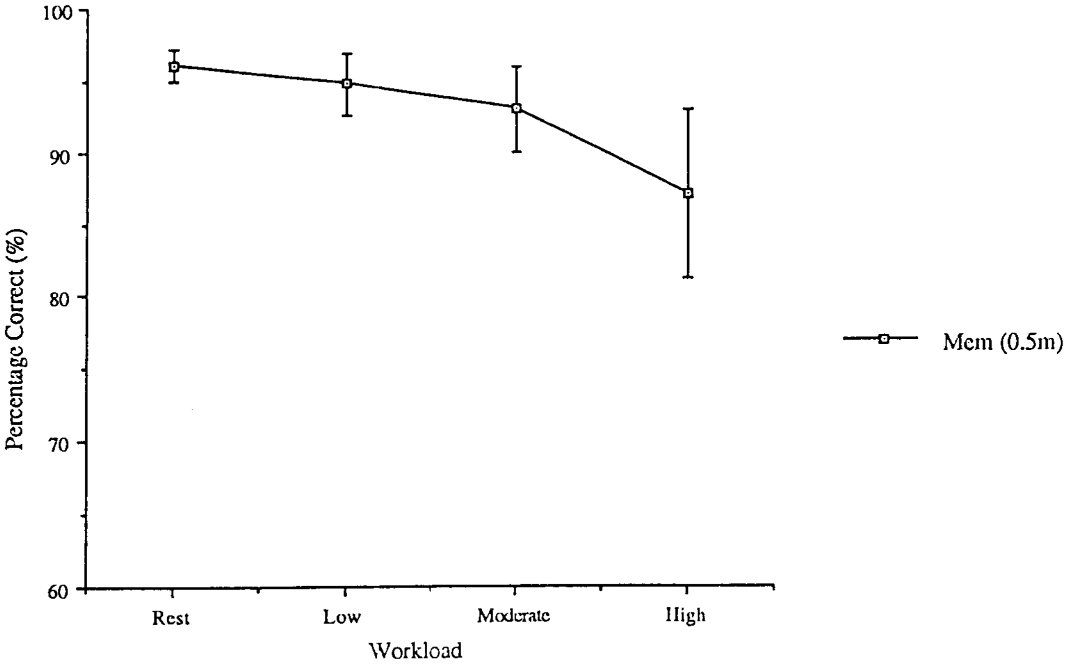

Figure 4.4A Exercise effect on short term memory (values are mean, bars are S.E.M.).

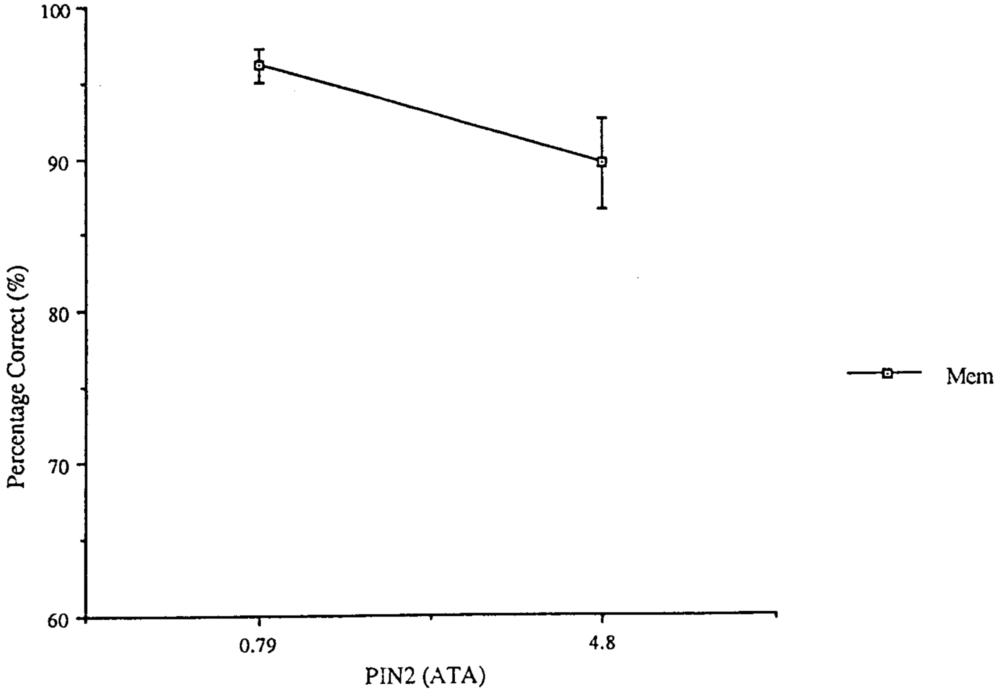

Figure 4.4B Nitrogen narcosis effect on short term memory (values are mean, bars are S.E.M.).

The presence of a significant workload effect (F=6.81, df=3,27, p<.005) indicates that the percentage of sequences recalled correctly varied across the workloads, when both pressures were considered together. Post hoc analysis revealed that the percentage of sequences recalled correctly at the highest workload was significantly less than at all other workloads. The mean percentage correct was 77% at the highest workload compared to 93%, 88% and 87% at rest, low and moderate workloads respectively.

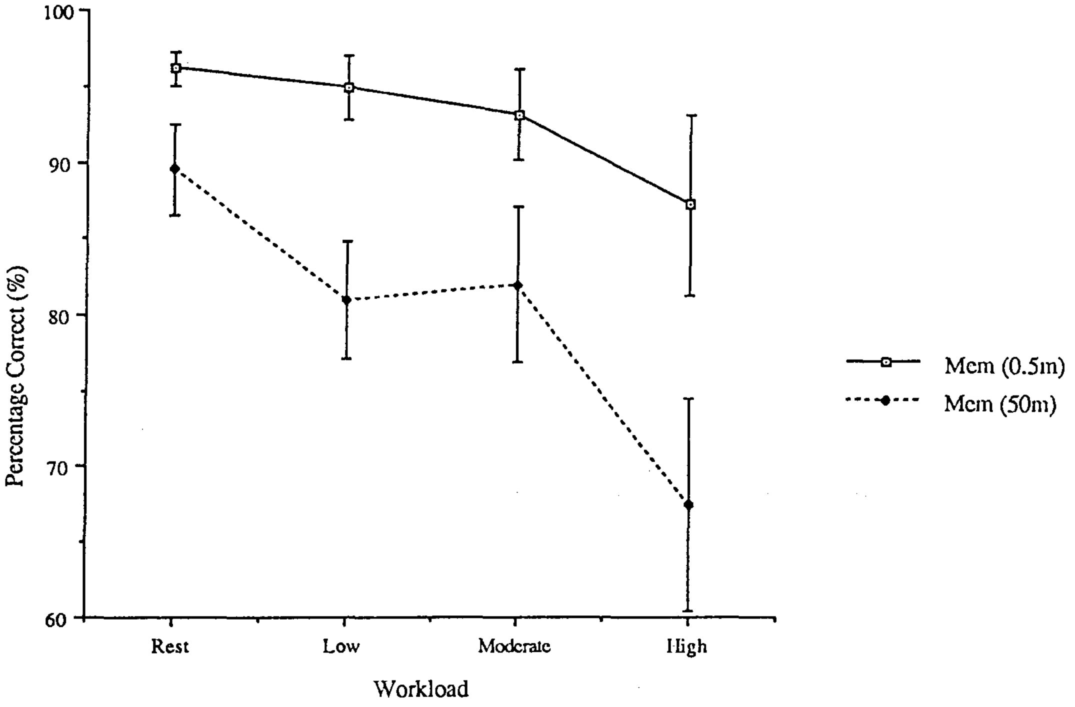

Figure 4.4C Combined effects of exercise, N_2 narcosis and exercise-induced hypercapnia on short term memory (values are mean, bars are S.E.M.).

4.3.2.3 Performance Decrements

The results of the four performance tests are expressed in terms of a performance decrement normalized to the 0.5 m results for the rest condition. The results are presented in Table 4.5 with the control results listed in the left hand column. Analysis of variance revealed that the main effect for test was not significant (F=0.55, df=3,27, p=.650), therefore the tests did not differ in their sensitivity between the conditions.

The bottom row of Table 4.5 displays the mean performance decrements for each of the conditions when the performance decrements were collapsed across all of the tests. The effect of an increase in the level of exercise is represented by the performance decrements at the low, moderate and high workloads at 0.5 m. It can be seen that increasing the level of exercise at 0.5 m resulted in a mean performance decrement of only 1.4% at the lowest workload, which gradually increased to a decrement of 3.6% at the highest workload (F=0.85, df=3,27, p=.481). Hence, there was no effect due to exercise, or the order of the workloads.

Table 4.5: Mean performance decrements for each experimental condition, for each test (n=10). Results are expressed in terms of a percent decrement (%) based on the mean 0.5 m results for the rest condition and listed under control values.

Performance	Control		0.5 m	(1 ATA)		50 m	(6 ATA)	
Test	Values	Low	Moderate	High	Rest	Low	Moderate	High
SRT (%)	262.4	0.08	6.3	5.5	2.8	8.7	8.2	21.8
(S.E.M.)	(7.7)	(5.2)	(5.7)	(7.5)	(5.5)	(5.1)	(5.3)	(9.7)
cCRT (%)	342.6	2.5	4.6	2.0	7.5	5.8	11.8	24.3
(S.E.M.)	(9.0)	(3.9)	(2.8)	(3.1)	(3.3)	(2.7)	(3.5)	(6.1)
iCRT (%)	403.4	2.0	-2.7	-2.4	8.1	3.7	9.0	18.2
(S.E.M.)	(9.7)	(3.3)	(1.7)	(3.9)	(5.3)	(2.8)	(4.4)	(6.0)
Mem (%)	96.1	1.2	3.2	9.3	6.9	15.7	14.7	29.9
(S.E.M.)	(1.1)	(2.2)	(3.1)	(6.1)	(3.1)	(4.0)	(5.3)	(7.3)
Mean Performance Decrement	------------	1.4%	2.8%	3.6%	6.3%	8.5%	10.9%	23.6%

The mean performance decrement was significant for the N_2 effect (F=7.23, df=1,9, p<.05), as shown by the results in the rest condition column at 50 m. An increase in the P_IN_2 from 0.79 ATA to 4.8 ATA under the rest condition resulted in a 6.3% decrement in performance. However, the most prominent effect was the combined effect of underwater exercise, N_2 narcosis and exercise-induced hypercapnia. A significant interaction effect was found between pressure and workload ($F=4.74$, $df=3,27$, $p<.01$) indicating that the change in performance decrement varied across the workloads between 0.5 and 50 m. *Post hoc* analysis revealed that the performance decrement observed at the highest workload at 50 m (23.6%) was significantly larger than all of the other performance decrements, both at 0.5 and 50 m.

4.3.2.4 Regression Analysis

One of the aims of this research was to examine the relationship between performance decrement, workload, P_IN_2 and $P_{ET}CO_2$. The dependent variable was percent decrement in performance and the independent variables considered were P_IN_2, workload and $P_{ET}CO_2$. The reason for including $P_{ET}CO_2$ as a possible variable was based on the hypothesis that the combined effects of N_2 narcosis and hypercapnia would cause significantly greater impairment than N_2 narcosis alone, and the experimental design, which projected that "the increasing levels of hypercapnia would be attained naturally as a result of the incremental workloads". Up to this point, $P_{ET}CO_2$ had not been directly considered as a factor in affecting performance, therefore regression analysis provided the opportunity. The data from all four tests were combined during stepwise regression analysis. The criterion of least squares (Shavelson, 1988) indicated that one independent variable accounted for a significant amount the common variance and that variable was $P_{ET}CO_2$. The other independent variables (P_IN_2 and workload) did not improve the fit of the relationship and therefore were not considered further.

A preliminary scatterplot of the performance decrement data against $P_{ET}CO_2$ showed some non-linearity to the relationship, therefore an exponential relationship was considered during the subsequent analysis. Multiple nonlinear regression analysis was performed on each of the four tests using the relationship shown below (4). For each of the four performance tests, the exponential relationship demonstrated an excellent fit to the data, accounting for between 80% and 94% of the common variance. The coefficients and R-squared values for equation (4), are listed below, for each of the performance tests.

$$\text{Percent Decrement} = A\, e^{k\,(\text{PETCO2})} - B \qquad (4)$$

Test	R^2	A	k	B
SRT	0.88	0.015	0.110	-0.436
cCRT	0.94	0.003	0.134	-1.399
iCRT	0.80	0.0002	0.174	0.035
Mem	0.87	0.490	0.066	6.425

Figure 4.5 illustrates the regression curves for each of the performance tests. The data points for each of the tests are represented by separate symbols for clarity. It can clearly be seen that all four tests showed similar trends when performance decrement was expressed as a function of $P_{ET}CO_2$.

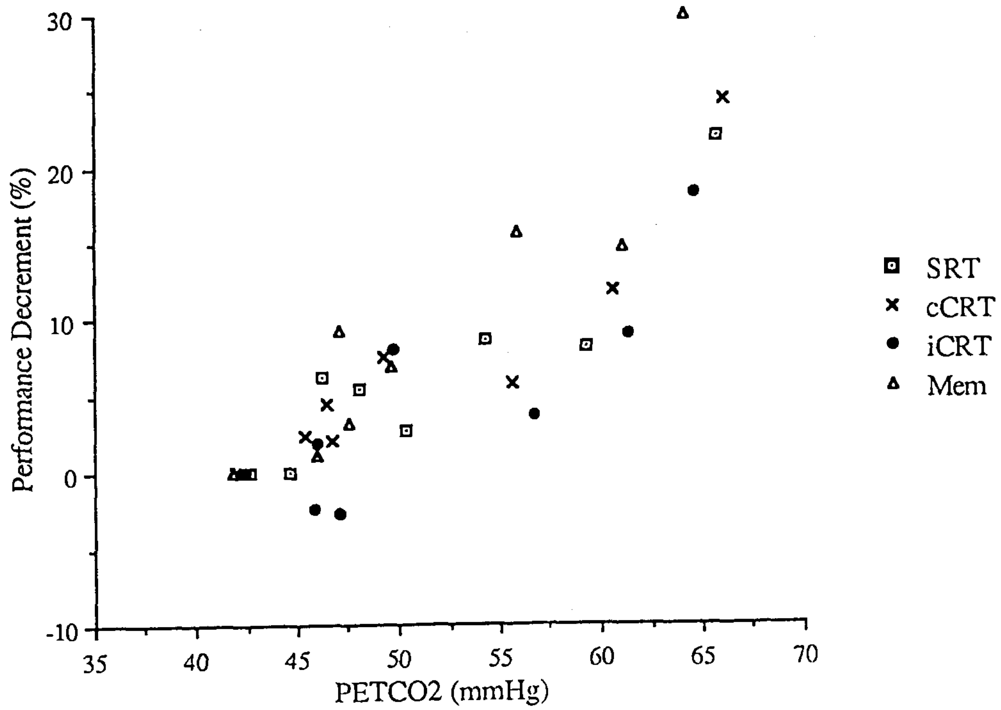

Figure 4.5 $P_{ET}CO_2$ versus the experimental performance decrements.

5.0 Discussion

In assessing diver performance, a number of factors may have influenced or affected the test results of this study other than the experimental factors of raised P_IN_2, hypercapnia, or underwater exercise. Some of these factors were related to the tests employed while others were related to the subject and/or the testing environment.

The effects of practice on performance were controlled by ensuring that a plateau of learning was achieved prior to the experimental sessions. Factors such as anxiety and motivation were difficult to control and even more difficult to assess (for a review, see Bachrach, 1975). In the present study the possibility of diving-related anxiety was minimized by conducting pre-experimental sessions to introduce and familiarize subjects to the sensation of underwater exercise at 50 m. In addition, all subjects had previous experience with underwater exercise and were certified divers. Attention, or the absence of attention, distraction, may also have affected performance at any given time; however, subjects were encouraged and reminded to concentrate on the test battery while ensuring that they maintained the workload, as monitored by the tender.

The experiments took place underwater, in a hyperbaric chamber where subjects were exposed to the intermittent noise of adjusting the chamber pressure. The chamber operators were instructed to adjust the pressure between the performance test sessions to avoid distraction by the valve noise. Subjects were required to wear a diving mask which may have reduced peripheral vision and presented as an influencing factor; however, there were no reports of reduced or limited vision. All subjects were exposed to the same main factors and any differences in adaptation to the performance tests or to the environmental conditions were controlled through a balanced repeated-measures design.

The present study adopted a realistic approach to studying the combined effects of underwater exercise, N_2 narcosis and exercise-induced hypercapnia on diver performance. In terms of the environment, the only change that would make the study more realistic would be to conduct the work in open-water conditions. The levels of underwater exercise chosen provided a natural means of attaining a range of end-tidal CO_2 levels at 0.5 and 50 m. The $P_{ET}CO_2$ levels ranged from 42-47 mmHg at 0.5 m to 49-65 mmHg at 50 m. The methodology did not allow for the isolation of the effects of hypercapnia at 50 m. However, in a practical diving situation the effects of N_2 narcosis and hypercapnia do not occur in isolation, instead they act in combination. Hence, the isolation of factors is not realistic.

5.1 Set Size and Stimulus-Response (S-R) Compatibility Effect

In the present study, reaction times were longer when the set size was increased from a single stimulus-response (S-R) alternative to four S-R alternatives, as proposed and demonstrated by Hick (1952). Hick's law is based on the increase in response latency observed when the number of S-R alternatives is increased. The present findings also showed that reaction times were longer when the compatibility of the S-R was low, which for the present study was when the stimulus and response positions were spatially opposite. This finding agrees with the work of Fitts and Seeger (1953) who published the classical demonstration of the compatibility effect. They showed that reaction time was fastest when the stimulus-response geometry corresponded directly. The effects of set size and compatibility on reaction time were evident across the workloads at 0.5 m, between the two levels of P_IN_2 and when the effects of workload and pressure were combined at 50 m.

5.2 Exercise Effect

End-tidal recordings of carbon dioxide tensions revealed no significant increase in the levels of exercise-induced hypercapnia at 0.5 m. Hence the effect of exercise on performance could be assessed with the subject underwater, at rest and during three progressive, sub-maximal workloads. Increasing levels of exercise did not significantly affect the speed or number of errors made during reaction time tasks. This finding does not support the Inverted-U hypothesis, which predicted that sub-maximal exercise would facilitate psychomotor performance at the low and moderate workloads yet would prove detrimental at the highest workload. Furthermore, a concomitant increase in the workload did not significantly affect the accuracy of recall during the short term memory test, despite physical exertion marked by a significant increase in heart rate. Since a significant exercise effect was not identified in any of the data, it can be concluded that the order of the workloads did not affect performance.

The physiological effects of exercise include changes in the cardiovascular, respiratory and musculo-skeletal systems. In addition to the physiological effects, it has been reported that physical activity alters the ability to perform motor tasks and also alters the capacity to perform mental tasks (Tomporowski and Ellis, 1986). It has been suggested that exercise "stimulates wakefulness" and increases arousal, in contrast to narcosis which acts as an anesthetic to decrease arousal (Adolfson, 1965, Davey 1974). Arousal, as defined by Schmidt (1988), refers to an internal state of alertness or excitement. It has been shown that exercise has autonomic effects similar to those associated with arousal; however, the mechanisms are not clearly defined (Tomporowski and Ellis, 1986).

The data on the effect of exercise on reaction time oppose the work of Babin (1968), Levitt and Gutin (1971) and Sjoberg (1977) who showed a curvilinear relationship between reaction time and exercise, hence arousal. The curvilinear relationship was termed the inverted-U hypothesis by Yerkes and Dodson (1908) and predicts an increase in the efficiency of motor performance with increasing arousal, up to an optimal point of physical arousal, which varies with the task, beyond which further increases in arousal result in a deterioration of motor performance. However, in many of the studies to-date, the levels of physical arousal have been inappropriately determined, poorly documented and in some cases the same workload was used for all subjects regardless of physical capacity. As a result, workloads were likely associated with different levels of physical arousal for different individuals. In their review of the effects of exercise on performance, Tomporowski and Ellis

(1986) stated that one of the most common shortcomings in studies is the use of overly simplistic measures of bodily function, such as absolute heart rate, as indices of general arousal state.

The present findings for reaction time agree with those of McGlynn and colleagues (1979) who used similar sub-maximal workloads and also noted that increasing level of exercise did not significantly affect the efficiency of motor performance. They expressed the workloads relative to the individuals' predicted maximal capacity and used the same measure as this study, that being percentage of maximal heart rate. The mean heart rates for the present study represented 40, 50, 60 and 75% of maximal heart rate, corresponding to rest, low, moderate and high workloads. McGlynn and others (1979) reported mean heart rates of 48, 59 and 74% or maximum. Their results indicated that at those levels of exercise, there was no significant effect on the speed or accuracy of performance on a discrimination task. They did observe a significant increase in speed when they exposed their subjects to a fourth stage of exercise where the exertion level was more intense, as indicated by a mean percentage maximal heart rate of 94%. The significant effect they observed at the most intense workload would, however, suggest an opposite effect to the Inverted-U hypothesis, where a decreased speed would be expected at that workload.

The second set of analyses yielded results similar to the reaction time tests, with no evidence of an exercise effect on short term memory. This finding supports the research hypothesis which predicted that cognitive function would not be affected by increasing levels of underwater, sub-maximal exercise. Research that has studied the relationship between exercise and mental performance had led to four possible outcomes; beneficial, detrimental, both beneficial and detrimental, or no effect at all (McGlynn et al, 1979). The third possibility describes the inverted-U hypothesis (Yerkes and Dodson, 1908), as discussed above. A limited number of studies have used short term memory testing and produced findings that were contradictory. However, the majority of studies show that mental abilities, including short term memory, are not affected by increasing levels of exercise (Fowler et al., 1985). Unfortunately, comparison of the present results for short term memory to those of other studies is made difficult by the fact that in most cases the memory tests were performed before and after, rather than during exercise. In assessing cognitive performance during exercise, it is possible that any beneficial effect of arousal is cancelled by a detrimental effect of dual-tasking during exercise due to the division of attention. The concept of limited information processing is based on the observation that an individual has difficulty doing two tasks simultaneously (Marteniuk, 1976). Hence, if performing a mental task, exercising and maintaining a workrate through position feedback all require a portion of the limited processing capacity within the central nervous system, then they may interfere with each other and performance of one or both may be hindered.

The present results disagree with the findings of Davey (1973) who used the Brown and Poulton mental test of attention, a test which relies heavily on short term memory, to assess the effect of exercise on mental performance. Davey (1973) found that mental performance improved during moderate physical exertion, while a detrimental outcome was observed during intense physical exertion. Their results therefore suggested a curvilinear relationship between arousal and mental performance, similar to the inverted-U hypothesis.

Sjoberg (1980) proposed a different theory in which the relationship between exercise and cognitive performance was dependent on the fitness level of the individual. He used a continual math function test that involved some short term memory and a paired association of words test to assess cognitive performance during and after sub-maximal exercise. His results revealed that exercise was detrimental on the performance of individuals that were in "poor" physical condition, whereas the "fit" individuals showed no effect whatsoever.

An alternative explanation for the findings of the present study relates arousal directly to attentional processes. Easterbrook's theory of attentional processes (1959) proposes that a change in physical arousal results in a concomitant change in attentional processes, such that an increase in arousal causes a shift or "narrowing" of attention to the central components of a task. The amount of attention devoted to the peripheral components of the task will be reduced with increasing arousal; therefore, the selection of "task-relevant" stimuli may be restricted to the point where performance will deteriorate. Based on the Easterbrook's theory (Easterbrook, 1959), changes in performance may not have been observed in the present study because it assessed central tasks, whereas arousal effects are more likely to affect peripheral tasks, which were not assessed. During the present study, some subjects showed improvement across the workloads, suggesting that they had ample attention to address both the memory test and complete the workloads, while other subjects showed large decrements in performance, particularly at the highest workload.

It is important to note that a literature search did not reveal any studies on the effects of increasing levels of underwater exercise on psychomotor and cognitive performance; therefore, the present results have been compared to research conducted in dry conditions. In addition, the tasks used in this study differed from those cited above, thereby making any comparisons somewhat tenuous. The obvious difference between the effects of exercise underwater versus exercise under dry conditions is the environment. It is likely that the novel physical factors encountered during underwater exercise may affect an individual's arousal level and thus performance. Weltman et al. (1970) identified the factors as lack of traction, restriction of vision and free-body positioning. During the present study, there were no subjective reports of difficulties with vision, traction or positioning. This was most likely due to the provision of a well-fitted mask and the ergonomically correct arrangement of the fin-ergometer and performance system.

5.3 Nitrogen Narcosis Effect

The present study exposed subjects to two levels of P_IN_2, 0.8 ATA at 0.5 m and 4.8 ATA at 50 m. Measurements of $P_{ET}CO_2$ under rest conditions at the two depths revealed that, although there was at least a 7 mmHg difference between the depths, this difference was not significant.

The presence of a nitrogen effect would be observed by the slope of the relationship between reaction time, number of errors, or score and P_IN_2. It was hypothesized that N_2 narcosis would produce a decrement in both cognitive and psychomotor performance. The collapsed performance decrement data for all four tests showed a significant N_2 effect during the rest condition. The results from the individual performance tests revealed a N_2 effect on three of the four tests. Although the collapsed data showed a significant decrement, the simple reaction time did not show evidence of a N_2 effect at the rest condition, due most likely to the small sample size $(n=10)$. However, the increase in the P_IN_2 to 4.8 ATA did affect the results of both the compatible and incompatible choice reaction time tests and the short term memory test, which supports the hypothesis that psychomotor and cognitive function was significantly affected by N_2 narcosis.

Analysis of the effect of an increase in P_IN_2 on error frequency revealed that there was no significant effect; however, subjects made significantly more errors when the S-R compatibility was low. These findings are supported by the work of Whitaker and Findley (1977) who also showed that error frequency did not increase when exposed to a similar P_IN_2 as in this study, yet they also found that individuals made more errors when the S-R compatibility was low. All of the findings agree with the classic work on S-R compatibility by Fitts and Seeger (1953).

The detrimental effect that exposure to increased levels of P_IN_2 exhibits on reaction time has been documented by numerous authors (Kiessling and Maag, 1962; Frankenhaeuser et al., 1963; Townsend et al., 1971; Whitaker and Findley, 1977; Fowler et al., 1982; Fowler et al., 1983; Fowler et al., 1989). In this study, the change in reaction time observed with the increase in P_IN_2 was proportionally the same for the compatible and incompatible choice reaction time tests. This indicates that the increased information-processing requirement of the incompatible S-R alternatives did not interact with the N_2

narcosis effect; hence, there was no difference in the susceptibility of the tests to narcosis. Whitaker and Findley (1977) showed identical results during a dive to approximately the same depth.

Research on the effects of N_2 narcosis on reaction time supports the present findings; however, the literature reveals a considerable discrepancy in the magnitude of the effect. The majority of studies conducted before 1980 express the effects of N_2 narcosis on performance in terms of a percent decrement. Expressing the results in terms of a percent decrement is inadequate for two reasons, as suggested by Stevens (1960). First, the percent decrement is dependent on the measurement scale used and second, the amount of variance in the performance data usually changes with the level of N_2 narcosis, which violates the required statistical assumption for comparing means. Despite these shortcomings, a similar approach was adopted for each of the performance tests used in the present study to facilitate the comparison of the results with those of previous studies.

In the present study, an increase in the P_IN_2 from 0.79 ATA to 4.8 ATA resulted in performance decrements of 7.5% and 8.1% for the compatible and incompatible choice reaction time tests, respectively. When the data were collapsed across the four tests, the increase in the P_IN_2 resulted in a mean performance decrement of 6.3%. These results fall within the lower part of the range of performance decrements documented by other researchers.

Studies that quantified the behavioural effect of increased inspired nitrogen partial pressures on simple reaction time reported performance decrements ranging from 2-3% at 50 m (Frankenhaeuser et al., 1963) to 20% at 30 m and 38% at 60 m (Townsend et al., 1971). The present magnitude of the change in simple reaction time agrees with the findings of Frankenhaeuser et al. (1963); however, the slowing in reaction time was not found to be significant.

The range of decrements for 2 and 4 choice reaction time tests was narrower, varying from 2-3% at 50 m (Frankenhaeuser et al, 1963) to 21% at 30 m (Kiessling and

Maag, 1962). The decrements in choice reaction time during the present study were approximately 8%, which exceeds the performance decrement shown by Frankenhaeuser and colleagues (1963) at the same depth, yet are less than the decrement shown by Kiessling and Maag (1962) at a shallower depth of 30 m. Reasons for the discrepancy in the effects of N_2 narcosis on the magnitude of the performance decrements may relate to the procedural differences between experiments; however, it is unlikely to be the complete explanation.

An alternative explanation for the variability in the performance decrements is based on the enhancing effect of CO_2 when some degree of narcosis is present. This explanation was recognized by Case and Haldane (1941) and various others. It is possible that the larger decrement noted by Kiessling and Maag (1962) was due in part to CO_2 contributing to the narcotic state of the individual during the test session. The results of the present study clearly indicated that when the effects of N_2 narcosis and hypercapnia were combined, the performance decrement was larger than the decrement noted with N_2 narcosis alone. The majority of studies on the behavioural effects of N_2 narcosis have not reported the $P_{ET}CO_2$ levels of the subjects during the performance testing, and it is unlikely that CO_2 tensions were measured. It has clearly been shown that an increase in ambient pressure, thus gas density, results in increased work of breathing (Lanphier and Camporesi, 1982). This, in addition to the elevated inspired O_2 pressure, results in elevated CO_2 levels. Even under resting conditions at depth, the $P_{ET}CO_2$ may exceed normal resting values of 35-40 mmHg, as was seen in the present study where the mean $P_{ET}CO_2$ was 49.7 mmHg at 50 m. Sayers et al. (1987) noted decreased speed of processing when the measured $P_{ET}CO_2$ exceeded the threshold he defined as 51 mmHg. It is plausible, therefore, that in previous studies CO_2 contributed to decrements which were attributed solely to N_2 narcosis.

The results of this study can be discussed in terms of the slowed processing model, as recommended by Fowler et al. (1985), which is a different approach to describing narcosis than the descriptive model used above. The present findings agree with the findings of Fowler and colleagues who have clearly shown that slowed reaction times are a central feature of the impairment in performance produced by inert gas narcosis (Fowler et al., 1985; Fowler, 1987; Fowler et al., 1988; Fowler et al., 1989; Fowler et al., 1990). Using the slowed processing model, narcosis causes slowing of information processing via a decrease in arousal, which is a functional variable within the information processing system. The slowing is shown to be nonspecific and is not localized to a particular processing stage, such as stimulus identification, response selection, or response programming. Although the arousal mechanism is unknown, Fowler and colleagues (1989) have recently proposed that the decrease in arousal modulates information via an early gating mechanism. They suggested that the activity of the mechanism is in turn dependent on the level of arousal.

It has typically been shown that the behavioural effects of narcosis also include a decreased accuracy of responding (Fowler et al., 1985). The present findings did not show a change in error frequency with an increase in P_IN_2, which is consistent with the findings of Fowler and colleagues (1985, 1989). Fowler's group has shown that the decrease in accuracy, or increase in error frequency, is actually due to a shift in the "speed-accuracy tradeoff". Typically, as individuals become more narcotic they sacrifice accuracy to maintain their speed of performance. The decrease in accuracy is not a distortion in the transmission of information but represents a secondary change in task strategy. Fowler suggested that when accuracy is controlled through practice or training (Fowler et al., 1985, 1989) the only effect of narcosis on performance is a slowing of reaction time.

It has been stated that there is considerable variability in the magnitude of the effect of an increase in P_IN_2 on performance decrements. It is possible that the speed-accuracy trade-off may explain part of the variation in the performance decrements noted by researchers in the area. The trade-off can alter performance results in two ways; either the individual can go faster and not worry about errors, as mentioned above, or he/she can go slower and be as accurate as possible. If the individual adopts the second alternative, then the result would likely be slower reaction times with no change in error rate, which would translate into larger performance decrements for the sake of maintaining accuracy.

The hypothesis predicted a decrement in cognitive function with the increase in P_IN_2 for the rest condition. The results revealed that there was a significant 6.9% decrement in performance on the short term memory test.

Cognitive function is a term which refers to a group of tasks involving mental processes including, decision making, information retrieval, short and long term memory, etc. (Adolfson and Berghage, 1974). Numerous cognitive function tests have been used to study the effects of N_2 narcosis on performance. Using tests of addition and grammatical reasoning, in addition to a number of others, Logie and Baddeley (1985) showed a mean performance decrement of 30% at 61 m, with the largest decrement noted on the math test. Fothergill et al. (1991) also showed significant decrements in mental performance at 50 m using a battery of cognitive tests, including a paired association memory test. It is therefore generally accepted that narcosis affects cognitive function; however, the effects differ according to the type of test used - short term memory, long term memory, or otherwise. The focus of this study is the effect of narcosis on short term memory.

Biersner (1972) reported a significant decrement in short term memory for logical material with exposure to 30% N_2O, while Fowler et al. (1973, 1985) concluded that short term memory is not impaired with narcosis, but long term memory is. The present results for the resting condition would tend to support the work of Biersner (1972). Furthermore, the combined effects on short term memory revealed that the scores were significantly lower at 50 m than they were at 0.5 m. Since it was shown that underwater exercise did not impair short term memory; then the decrease in the scores at 50 m may be attributed to the combined effect of CO_2 and N_2 narcosis. This would also suggest that short term memory was affected by narcosis, which does not support Fowler et al. (1973, 1985).

Some of the earlier studies on the behavioural effects of narcosis supported a model known as the hierarchical organization hypothesis (Kiessling and Maag, 1962; Biersner et al., 1978; and Hesser et al., 1978). The model proposes that the sensitivity of physiological systems to anesthetic depends on the phylogenetic age (Himwich, 1951); thus, newer higher centers are likely to be more sensitive and therefore, affected first. When applied to narcosis, the hypothesis predicts that the greater the complexity of a test, the more it will be affected by narcosis. The tests used in the present study included reaction time tests and a test of short term memory; however, despite the differences in the amount of information processing for the different tests, there was no evidence of differing sensitivities between the tests with exposure to increased N_2 pressures. The present findings do not support the theory and therefore are in agreement with Fowler (1985), who faults the model on the basis that determining the complexity of task is an unreliable way of differentiating between tests.

5.4 Combined Effects; Exercise, N_2 Narcosis and Exercise-induced hypercapnia

A review of the literature revealed a lack of quantitative data on the combined effects of underwater exercise, exercise-induced hypercapnia and N_2 narcosis on diver performance. As outlined by the methodology of the study, the increasing levels of exercise at depth served only to increase the level of hypercapnia through a natural, physiological mechanism. The results demonstrated that there was no apparent exercise effect on psychomotor and cognitive performance; therefore, this section will discuss the combined effects of hypercapnia and N_2 narcosis on performance.

The combined effect would be represented by an interaction effect, whereby the slope of the relationship between the performance measure (reaction time, error frequency, or score) and the increase in workload differed between the 0.5 and the 50 m experiments. An increase in the slope at 50 m would indicate that the combined effects of N_2 narcosis and exercise-induced hypercapnia resulted in a greater deterioration of psychomotor and cognitive performance than the effect observed for N_2 narcosis alone.

The results lend support to the hypothesis that the combined effects resulted in a significantly greater performance decrement than the decrement observed with N_2 narcosis alone. Fifty years ago, Case and Haldane (1941) reported similar findings when they exposed subjects to the combined effects of hypercapnia and N_2 narcosis, but at higher levels of hypercapnia and pressure than those observed for the present study. They found that the combined effects were much more severe than the effect of either CO_2 or N_2 narcosis alone. At 100 m, subjects breathing F_ICO_2 levels greater than 6% gradually lost consciousness while working at their assigned tasks. Other studies on the combined effects of hypercapnia and N2 narcosis have found similar results on diver performance at shallower depths and lower CO_2 levels (Hesser et al., 1971, 1978; Fothergill et al., 1991).

A review of the literature did not reveal any studies on the combined effects of hypercapnia and N_2 narcosis on reaction time and produced only two studies on the isolated effect of hypercapnia on simple reaction time. Slowed reaction time is a central feature of the performance impairment observed with narcosis (Fowler et al., 1985). However, the simple reaction time test did not show any evidence of a significant N_2 effect when exposed to a P_IN_2 of 4.8 ATA. Although reaction times were longer for the simple reaction time test when the level of hypercapnia increased at 50 m, the 21.8% performance decrement was not significant. Since it has been shown that CO_2 narcosis and N_2 narcosis combine in an additive manner to affect performance (Hesser et al., 1971, 1978; Fowler et al., 1985; Fothergill et al., 1991), the present results do not reflect the expectation that reaction times should have slowed significantly as the $P_{ET}CO_2$ increased at 50 m. However, the results agree with those of Sheehy et al. (1982), who measured the effects of hypercapnia on subjects breathing 4 and 5% CO_2 while exercising at sub-maximal workloads. Although Sheehy et al. (1982) did not report the measured $P_{ET}CO_2$, they showed that auditory simple reaction time did not change under conditions of hypercapnia. Henning and others (1990) exposed their subjects to higher inspired levels of CO_2 (6%) without exercise and recorded a mean $P_{ET}CO_2$ of 50 mmHg, yet they too found that simple reaction time did not change under conditions of hypercapnia. Based on their findings and those of Sheehy et al (1982), they concluded that inspired levels of 0-5% CO_2 did not affect reaction time and recommended further study on the performance effects of breathing 6-10% CO_2. The levels of hypercapnia during the present study exceeded those documented by other researchers on the behavioural effects of CO_2, and likely approached levels of hypercapnia that an individual may experience when inspiring 6-10% CO_2 (Sayers et al., 1987). Even with this level of inspired CO_2, simple reaction time still showed no statistically significant effect with ANOVA.

The majority of studies which have considered the combined effects of hypercapnia and N_2 narcosis have employed traditional paper and pencil tests (Fowler et al., 1985; Fothergill et al., 1991). Since a slowing of reaction time was noted for the choice reaction time tests when exposed to an increase in P_IN_2, it follows that a further decrement would be observed as the level of hypercapnia increase, which is supported by the present data.

The present findings agree with Sheehy et al. (1982), who also considered the effects of inspired CO_2 and exercise-induced hypercapnia on a choice reaction time test. In contrast to their results for the simple reaction time test, choice reaction time showed a significant slowing when the inspired fraction of CO_2 was 5%. The present findings do not agree with the results of Henning et al. (1990) who, despite using higher levels of inspired CO_2, did not show any significant effect on choice reaction time. The likely reason for the difference between the results of the two studies is that the $P_{ET}CO_2$ levels were probably higher during the study by Sheehy et al. (1982) due to the internal production of the CO_2 during sub-maximal exercise. Henning et al. (1990) reported a mean $P_{ET}CO_2$ of 50 mmHg, which according to Sayers et al. (1987) is below the threshold for observing performance effects. Sayers and colleagues (1987) noted a decrease in the speed of performing a subtraction and logic tests when the alveolar (or end-tidal) CO_2 levels exceeded 51 mmHg.

The number of errors made during the choice reaction time tests did not change with the increase in workload or pressure. These results are in agreement with the findings on the effects of N_2 narcosis and CO_2 narcosis on error frequency. It has been shown that increased levels of $P_{ET}CO_2$ are associated with a slowing of information processing. However the decrease in speed is not accompanied by a change in accuracy (Hesser et al., 1971; Sayers et al., 1989; Fothergill et al., 1991), as is the case during the present study.

The second set of analyses revealed significant main effects for pressure and workload on short term memory. The main effect for workload revealed a decrease in score with the increase in workload. The pressure effect indicated that, overall, scores were lower at 50 m as compared to 0.5 m, therefore a N_2 effect was observed but not an exercise effect. In contrast to the reaction time tests, the results for the short term memory test did not show a significant interaction effect between workload and pressure.

Research on the effects of hypercapnia on short term memory by Sheehy et al. (1982) showed that inspired levels of CO_2 below 5% do not affect short term memory. Henning and colleagues also showed a lack of evidence of an effect on short term memory with inspired CO_2 levels up to 6%, corresponding to a $P_{ET}CO_2$ of approximately 50 mmHg (Henning et al., 1990). Realistically, divers may exhibit $P_{ET}CO_2$ levels above 70 mmHg (Morrison et al., 1981); therefore, testing should be conducted at higher levels of inspired CO_2. Sayers et al. (1987) exposed their subjects to inspired levels of 7.5% CO_2 at atmospheric pressure, and showed a small but insignificant performance decrement on a short term memory test. They planned to expose the subjects to higher levels but found that levels above 7.5% could not be tolerated by subjects without discomfort. The present study exposed divers to $P_{ET}CO_2$ levels comparable with those of Sayers et al. (1987). Although the scores decreased with the increase in $P_{ET}CO_2$ at 50 m, the change was not significantly different from the change observed with increasing workload at 0.5 m using ANOVA. When the short term memory scores were correlated with $P_{ET}CO_2$ and P_IN_2, it was found that $P_{ET}CO_2$ accounted for a significantly larger amount of the common variance than P_IN_2 ($Z=2.408$, $p<.05$) using Fisher's Z transformation (Shavelson, 1988). This would suggest that the significant decrease in the scores at 50 m was related to the combined effects of N_2 narcosis and hypercapnia.

As alluded to earlier, this study did not allow isolation of the effects of hypercapnia on performance; however, Hesser and colleagues (1971) assessed the relationship between CO_2 narcosis and N_2 narcosis and concluded that the effects were additive. Further support for the additive effect was provided by a subsequent study by Hesser et al. (1978). They found that hypercapnia and N_2 narcosis were additive for mental arithmetic, or cognitive function. In contrast, hypercapnia degraded manual dexterity, or psychomotor function, but N_2 narcosis did not. These findings led them and others (Fowler et al., 1989; Fothergill et al., 1991), to suggest that the mechanism underlying CO_2 narcosis is different from that of N_2 narcosis.

There are varying hypotheses of the physiological mechanism of hypercapnia on performance. Hesser et al. (1978) hypothesized that the narcotic effect of CO_2 was mediated by hydrogen ions based on their own findings and the work of Eisele et al. (1967). Eisele and co-workers showed that the anesthetic effect of CO_2 correlated better with the acidity level of cerebrospinal fluid rather than arterial CO_2 tensions. The earlier work by Meyer et al. (1961) also showed a strong correlation between electrical activity of the encephalon and cortical pH, and they suggested that the increased acidity causes a reversible suppression of the sodium extrusion pump. There is still some uncertainty regarding the mechanism of the effects of CO_2 narcosis on performance.

Bennett (1964) indicated that the inert gases, such as N_2, act primarily on the parts of the nervous system that are rich in synapses. In his review on the area (Bennett, 1982) he suggested that the most likely site of action would be the lipid layer in the mitochondria and hypothesized that inert gas narcosis is the result of interference with central synaptic transmission. Based on the experiments of others, as reviewed by Bennett (1982), it was inferred that a fundamental change takes place at polysynaptic sites in the brain when a critical tension of nitrogen, or any of the other inert gases, is exceeded. The manifestations of the change may be observed in the form of performance effects.

One of the eventual goals of this research was to describe the relationship between performance decrement, underwater exercise, N_2 narcosis and exercise-induced hypercapnia. The regression equations presented such a relationship in the form of a non-linear exponential equation which predicts performance decrements based on $P_{ET}CO_2$. The equations demonstrated an excellent fit to the data accounting for between 80% and 94% of the common variance between performance decrement and $P_{ET}CO_2$.

Researchers have postulated the presence of thresholds for the combined effects of hypercapnia and N_2 narcosis at hyperbaric pressures (Hesser et al, 1971, 1978). However, the non-linearity of the present findings suggest that the proposed thresholds may have been identified without awareness of the relationship over the physiological range of the variables. The proposed relationship (Equation 4) was based on a range of mean $P_{ET}CO_2$ levels varying from 41.9 mmHg; a normal resting value, to 66.9 mmHg; and a value which surpasses the 60 mmHg level where definite signs of CO_2 intoxication are usually evident (Lanphier, 1975). The present range of $P_{ET}CO_2$ represents a physiological range which may be attained by divers working at sub-maximal levels of exertion in the hyperbaric environment.

If the data presented as Figure 4.5 were analyzed as two separate curves, one relating the combined performance decrements at 0.5 ATA to $P_{ET}CO_2$ and the other relating the 50 m data to $P_{ET}CO_2$, different relationships might demonstrate a better fit to the data. When a linear relationship was fit to the 0.5 m data, the result was a poorly fitting equation which accounted for a non-significant 23% of the common variance between performance decrement and $P_{ET}CO_2$ ($F=4.18$, $p=.060$). The 50 m data exhibited $P_{ET}CO_2$ levels greater than 49 mmHg and progressing to 67 mmHg. Over the range of the 50 m data, the relationship between $P_{ET}CO_2$ and the combined performance decrements is clearly non-linear, as defined by an exponential equation ($R^2=0.69$). This observation of a non-linear relationship makes it more difficult to identify a threshold. Furthermore, if a threshold exists for CO_2 narcosis and/or N_2 narcosis, it is probable that a threshold for one factor would vary in the presence of the other factor.

The present study stresses the marked effect that hypercapnia demonstrates on psychomotor and cognitive performance. When the changes in performance are expressed in terms of performance decrements, the combined effects of underwater exercise, N_2 narcosis and exercise-induced hypercapnia resulted in significantly larger performance decrements than the effect observed with N_2 narcosis alone. The data shown in Figure 4.5, the non-linear relationship between $P_{ET}CO_2$ and performance decrement, provides an indication of the deterioration in performance to be expected in a diver working underwater at 50 m. The regression analysis also suggests that the deterioration observed was primarily a function of exercise-induced hypercapnia in response to increased gas density.

5.5 Recommendations for Future Research

Since a review of the literature revealed no studies on the effects of underwater exercise on performance, additional studies are highly recommended.

Emphasis has been placed on the practical approach of the present study to assessing the combined effects of underwater exercise, N_2 narcosis and exercise-induced hypercapnia on diver performance. The present methodology did not allow for the isolation of the effect of hypercapnia on performance. The methodology of previous studies considered both the isolated effects of hypercapnia and N_2 narcosis on performance and the combined effect (Hesser et al., 1971, 1978; Fothergill et al., 1991); however, experiments were conducted at rest in a dry hyperbaric chamber. It is recommended that future research on both the isolated and the combined effects of hypercapnia and N_2 narcosis on diver performance be conducted under realistic diving conditions.

The present study identified a non-linear relationship between hypercapnia and performance that has not been reported previously. Hence, the innovation of this finding alone suggests that further study is needed of the combined effect of hypercapnia and N_2 narcosis on performance.

6.0 Summary and Conclusions

The purpose for employing divers is to accomplish a task, or perform useful work, in the underwater environment. Due to the severity of physical stressors, the emphasis has been on getting the diver safely to and from the work site, rather than on the work itself. However, it is equally important that the diver, while working under raised ambient pressure, be physically and mentally capable of performing the work expeditiously, accurately and safely.

The present study took a practical approach to assessing the combined effects of underwater exercise, N_2 narcosis and exercise-induced hypercapnia on diver performance. The test battery included reaction time tests and a short term memory test. All of the tests assessed specific elements of tasks that a diver may be responsible for performing while working underwater at depth. Furthermore, the levels of underwater exercise provided a natural means of attaining a range of $P_{ET}CO_2$ levels. The methodology of this study did not allow for the isolation of the effects of hypercapnia on performance; however, it is unlikely that a working diver would be exposed to the effects of N_2 narcosis or hypercapnia, exclusively.

The combined effects of N_2 narcosis and exercise-induced hypercapnia were shown to have a significant effect on psychomotor and cognitive performance, more so than the effect observed with N_2 narcosis alone. This finding supports the hypothesis and previous studies that examined the combined effects (Case and Haldane, 1941; Hesser et al., 1971, 1978; Fothergill et al., 1991); however, the present study is the only one to assess the combined effects on performance in a practical diving environment.

The measured mean $P_{ET}CO_2$ ranged from 42-47 mmHg at 0.5 m and to 49-65 mmHg at 50 m. There was no evidence of a change in psychomotor or cognitive performance during exposure to increased levels of underwater exercise at 0.5 m. When the subjects were at rest underwater at 50 m, the increase in P_IN_2 resulted in a significant slowing of choice reaction time with no change in the number of errors made. There was a significant decrease in the accuracy of recall during a short term memory test under the same conditions, with significantly lower scores on the short term memory test at 50 m, indicating that a N_2 effect was present. The largest decrements in performance were observed at the highest workloads at 50 m, where the mean $P_{ET}CO_2$ level was 65 mmHg. The pooled performance decrement data from all four tests did not reveal an exercise effect, but exhibited a significant N_2 narcosis effect and a significant combined CO_2 and N_2 narcosis effect, as shown by the significant interaction effect between workload and pressure.

The data presented in Figure 4.5 provides a means to identify the susceptibility of diver performance to the combined effects of N_2 narcosis and hypercapnia. A review of the literature revealed that the relationship between the combined effects of hypercapnia and N_2 narcosis and performance has not been previously defined in terms of a non-linear equation. Previous studies have reported thresholds for hypercapnia (Sayers, 1987), N_2 narcosis (Kiessling and Maag, 1962; Poulton et al., 1964; Bennett, 1982) and the combined effects of CO_2 narcosis and N_2 narcosis (Hesser et al., 1971, 1978) beyond which performance decrements were reported. The observation of a non-linear relationship, as described by the present study, would make it more difficult to identify a threshold. A non-linear relationship does not preclude the presence of a threshold. However, it is probable that if a threshold were identified for CO_2 narcosis and N_2 narcosis, the threshold of one of the factors would vary with the presence of the other factor.

Appendix A: ANOVA Tables for Performance Test Data

Exercise Effect (R, L, M, H at 0.5 m)

Set Size (Simple RT versus Compatible Choice RT)

Source	SS	df	MS	F	Sig of F
Mean	7701646.05	1	7701646.1	1479.81	000
Subjects	46840.20	9	5204.47		
Workload (W)	2997.05	3	999.02	1.14	.349
Subects	23578.70	27	873.29		
Test (T)	128480.45	1	128480.45	47.34	.000
Subjects	24425.80	9	2713.98		
W x T	621.45	3	207.15	0.23	.873
Subjects	24098.30	27	892.53		

S-R Compatibility (Compatible versus Incompatible Choice RT)

Source	SS	df	MS	F	Sig of F
Mean	11268757.81	1	11268758	2103.02	.000
Subjects	48225.31	9	5358.37		
Workload (W)	1042.34	3	347.45	0.73	.542
Subjects	12804.04	27	474.22		
Test (T)	49850.11	1	49850.11	45.37	.000
Subjects	9889.01	9	1098.78		
W x T	2508.44	3	836.15	1.01	.402
Subjects	22257.94	27	824.37		

Exercise Effect (R, L, M, H at 0.5 m)

S-R Compatibility Errors (as above)

Source	SS	df	MS	F	Sig of F
Mean	1402.81	1	1402.81	11.04	.009
Subjects	1144.06	9	127.12		
Workload (W)	10.94	3	3.65	.22	.884
Subjects	454.69	27	16.84		
Test (T)	25.31	1	25.31	.77	.404
Subjects	296.56	9	32.95		
W x T	68.44	3	22.81	1.91	.151
Subjects	322.19	27	11.93		

Short Term Memory

Source	SS	df	MS	F	Sig of F
Mean	344102.50	1	344102.50	1364.28	.000
Subjects	2270.00	9	252.22		
Workload (W)	474.10	3	158.03	2.00	.137
Subjects	2131.40	27	78.94		

Nitrogen Effect (R at 0.5 versus R at 50 m)

Set Size (Simple RT versus Compatible Choice RT)

Source	SS	df	MS	F	Sig of F
Mean	3863244.02	1	3863244.02	1999.01	.000
Subjects	17393.23	9	1932.58		
Pressure (P)	2739.02	1	2739.02	2.80	.129
Subjects	8813.22	9	979.25		
Test (T)	79834.22	1	79834.22	48.26	.000
Subjects	14887.03	9	1654.11		
P x T	837.23	1	837.23	4.27	.069
Subjects	1765.02	9	196.11		

S-R Compatibility (Compatible versus Incompatible Choice RT)

Source	SS	df	MS	F	Sig of F
Mean	6008575.22	1	6008575.22	1401.31	.000
Subjects	38590.53	9	4287.84		
Pressure (P)	8497.23	1	8497.23	6.55	.031
Subjects	11680.53	9	1297.84		
Test (T)	41280.62	1	41280.62	34.57	.000
Subjects	10748.13	9	1194.24		
P x T	119.02	1	119.02	.15	.711
Subjects	7313.73	9	812.64		

Nitrogen Effect (R at 0.5 versus R at 50 m)

S-R Compatibility Errors (as above)

Source	SS	df	MS	F	Sig of F
Mean	810.00	1	810.00	38.37	.000
Subjects	190.00	9	21.11		
Pressure (P)	22.50	1	22.50	1.59	.239
Subjects	127.50	9	14.17		
Test (T)	160.00	1	160.00	16.00	.003
Subjects	90.00	9	10.00		
P x T	22.50	1	22.50	.89	.370
Subjects	227.50	9	25.28		

Short Term Memory

Source	SS	df	MS	F	Sig of F
Mean	172236.90	1	172236.90	2843.23	.000
Subjects	545.20	9	60.58		
Pressure (P)	217.80	1	217.80	6.05	.036
Subjects	324.20	9	36.02		

Combined Effect (R, L, M, H at 0.5 m and 50 m)

Set Size (Simple RT versus Compatible Choice RT)

Source	SS	df	MS	F	Sig of F
Mean	16770897.51	1	16770897.51	2230.25	.000
Subjects	67677.56	9	7519.73		
Pressure (P)	29079.06	1	29079.06	5.17	.049
Subjects	50647.51	9	5627.50		
Workload (W)	24649.02	3	8216.34	9.58	.000
Subjects	23161.17	27	857.82		
Test (T)	307563.91	1	307563.91	40.11	.000
Subjects	69018.91	9	7668.77		
P x W	14138.67	3	4712.89	4.11	.016
Subjects	30976.02	27	1147.26		
T x W	2272.56	1	2272.56	3.16	.109
Subjects	6478.76	9	719.86		
W x T	319.32	3	106.44	.09	.966
Subjects	32674.12	27	1210.15		
P x W x T	2661.07	3	887.02	1.12	.358
Subjects	21359.87	27	791.11		

Combined Effect (R, L, M, H at 0.5 m and 50 m)

S-R Compatibility (Compatible versus Incompatible Choice RT)

Source	SS	df	MS	F	Sig of F
Mean	24907941.51	1	24907941.51	955.22	.000
Subjects	114652.81	9	12739.20		
Pressure (P)	59251.51	1	59251.51	9.77	.012
Subjects	54582.56	9	6064.73		
Workload (W)	16661.22	3	5553.74	5.51	.004
Subjects	27226.72	27	1008.40		
Test (T)	116262.31	1	116262.31	41.80	.000
Subjects	25029.76	9	2781.08		
P x W	26413.72	3	8804.57	7.95	.001
Subjects	29900.47	27	1107.42		
P x T	636.01	1	636.01	2.51	.147
Subjects	2276.31	9	252.92		
W x T	2341.92	3	780.64	.88	.465
Subjects	24028.27	27	889.94		
P x W x T	912.92	3	304.31	.40	.756
Subjects	20687.02	27	766.19		

Combined Effect (R, L, M, H at 0.5 m and 50 m))

S-R Compatibility Errors (Compatible versus Incompatible Choice RT)

Source	SS	df	MS	F	Sig of F
Mean	3610.00	1	3610.00	14.86	.004
Subjects	2186.88	9	242.99		
Pressure (P)	50.62	1	50.62	1.95	.196
Subjects	233.75	9	25.97		
Workload (W)	16.25	3	5.42	.25	.861
Subjects	586.88	27	21.74		
Test (T)	180.63	1	180.63	4.03	.076
Subjects	403.75	9	44.86		
P x W	48.13	3	16.04	.76	.525
Subjects	567.50	27	21.02		
P x T	40.00	1	40.00	1.98	.193
Subjects	181.88	9	20.21		
W x T	63.12	3	21.04	1.73	.184
Subjects	327.50	27	12.13		
P x W x T	46.25	3	15.42	1.36	.277
Subjects	306.88	27	11.37		

Short Term Memory

Source	SS	df	MS	F	Sig of F
Mean	596333.11	1	596333.11	1007.18	.000
Subjects	5328.76	9	244.81		
Pressure (P)	3289.61	1	3289.61	13.44	.005
Subjects	2203.26	9	244.81		
Workload (W)	2557.44	3	852.48	6.81	.001
Subjects	3381.19	27	125.23		
P x W	450.74	3	150.25	1.78	.175
Subjects	2278.89	27	84.40		

ANOVA Tables on Performance Decrement Data (%)

Exercise Effect (R, L, M, H at 0.5 m)

Source	SS	df	MS	F	Sig of F
Mean	622.90	1	622.90	1.04	.335
Subjects	5403.03	9	600.34		
Workload (W)	307.69	3	102.56	.85	.481
Subjects	3276.85	27	121.36		
Test (T)	430.49	3	143.50	.50	.687
Subjects	7794.55	27	288.69		
W x T	804.05	9	89.34	1.16	.329
Subjects	6214.54	81	76.72		

Nitrogen Effect (R at 0.5 m versus R at 50 m)

Source	SS	df	MS	F	Sig of F
Mean	799.71	1	799.71	3.34	.101
Subjects	2154.35	9	239.37		
Pressure (P)	799.71	1	799.71	7.23	.025
Subjects	995.78	9	110.64		
Test (T)	85.36	3	28.45	.17	.916
Subjects	4522.71	27	167.51		
P x T	85.37	3	28.46	.53	.664
Subjects	1441.66	27	53.39		

ANOVA Tables on Performance Decrement Data (%)

Combined Effect (R, L, M, H at 0.5 m and 50 m)

Source	SS	df	MS	F	Sig of F
Mean	16330.37	1	16330.37	19.56	.002
Subjects	7512.08	9	834.68		
Pressure (P)	8555.22	1	8555.22	10.03	.011
Subjects	7677.59	9	853.07		
Workload (W)	4992.97	3	1664.32	12.66	.000
Subjects	3548.27	27	131.42		
Test (T)	1288.60	3	429.53	.55	.650
Subjects	20925.47	27	775.02		
P x W	2475.10	3	825.03	4.74	.009
Subjects	4704.47	27	174.24		
P x T	357.44	3	119.15	.87	.467
Subjects	3683.61	27	136.43		
W x T	925.29	9	102.81	.94	.497
Subjects	8872.77	81	109.54		
P x W x T	642.13	9	71.35	1.00	.445
Subjects	5766.29	81	71.19		

Appendix B; ANOVA Tables on Physiological Data

(R,L,M,H at 0.5 m and 50 m)

End-tidal Carbon Dioxide ($P_{ET}CO_2$)

Source	SS	df	MS	F	Sig of F
Mean	213000.67	1	213000.67	761.55	.000
Subjects	2517.25	9	279.69		
Pressure (P)	3048.72	1	3048.72	65.71	.000
Subjects	417.60	9	46.40		
Workload (W)	1144.82	3	381.61	34.29	.000
Subjects	300.46	27	11.13		
P x W	317.52	3	105.84	20.95	.000
Subjects	136.42	27	5.05		

Ventilation (V_E)

Source	SS	df	MS	F	Sig of F
Mean	69129.40	1	69129.40	479.93.	000
Subjects	1296.38	9	144.04		
Pressure (P)	9.02	1	9.02	.69	.429
Subjects	118.53	9	13.17		
Workload (W)	9822.57	3	3274.19	203.03	.000
Subjects	435.42	27	16.13		
P x W	188.17	3	62.72	5.14	.006
Subjects	329.54	27	12.21		

ANOVA Tables on Physiological Data

Tidal Volume (V_t)

Source	SS	df	MS	F	Sig of F
Mean	542.93	1	542.93	203.49	.000
Subjects	24.01	9	2.67		
Pressure (P)	.13	1	.13	.31	.590
Subjects	3.81	9	.42		
Workload (W)	6.67	3	2.22	25.73	.000
Subjects	2.33	27	.09		
P x W	1.22	3	.41	5.55	.004
Subjects	1.97	27	.07		

Breathing Frequency (B_f)

Source	SS	df	MS	F	Sig of F
Mean	10998.05	1	10998.05	174.28	.000
Subjects	567.95	9	63.11		
Pressure (P)	.20	1	.20	.02	.885
Subjects	81.30	9	9.03		
Workload (W)	843.75	3	281.25	67.65	.000
Subjects	112.25	27	4.16		
P x W	.40	3	.13	.05	.987
Subjects	78.10	27	2.89		

Heart Rate (HR)

Source	SS	df	MS	F	Sig of F
Mean	808824.20	1	808824.20	943.57	.000
Subjects	7714.80	9	857.20		
Pressure (P)	911.25	1	911.25	5.64	.042
Subjects	1455.25	9	161.69		
Workload (W)	43939.70	3	14646.57	220.27	.000
Subjects	1795.30	27	66.49		
P x W	335.45	3	111.82	8.58	.000
Subjects	352.05	27	13.04		

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