A cross-over study investigating specific aspects of neuropsychological performance in hyperbaric environments

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DECLARATION

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ABSTRACT

The commercial and military deep diving environment is typically a low visibility environment, where dependence on the visual senses often needs to be replaced by a reliance on tactile senses.

This thesis reviewed the current knowledge regarding neuropsychological manifestations of nitrogen narcosis and exposed a number of shortcomings in the current body of knowledge. In particular, the human performance effects of hyperbaric exposure on tactile perception and memory have not been systematically studied. It is further not clear, how exactly psychological factors (e.g. anxiety, mood states) and biographical factors (e.g. age, education, technical exposure, experience) might influence tactile perception and memory performance under conditions of hyperbaric exposure. The correlation between subjective experiences of narcosis, tactile performance, and psychological and biographical variables is also unknown. This study thus set out to investigate certain neuropsychological aspects of nitrogen narcosis, with special reference to tactile perception and memory, and to examine the relationships of tactile performance with other psychological and biographical factors.

The effects of experimental hyperbaric exposure (EHE) on tactile (form) perception and tactile shape memory were examined by testing these functions at 6 ATA and 1 ATA, using a cross-over design where two groups completed the same tasks, in opposite sequence. The psychological variables included trait anxiety, transient mood states, and subjective ratings of narcosis, while the biographical variables included age, education, and previous technical exposure.

The results demonstrated the detrimental effect of nitrogen narcosis on tactile form perception and manipulation, irrespective of the sequence of testing. It also demonstrated this effect on tactile form memory, although the sequence of testing also played a role here.

Higher trait anxiety was associated with poorer recall, and tension was associated with a larger decrement in recall performance, while fatigue was associated with poorer task completion. Subjective experiences also played a role, where feelings of physical anxiety (i.e. increased arousal) were associated with better recall, and feelings of cognitive suppression (decreased arousal) were associated with a larger decrement in recall performance. Lower academic attainment was associated with poorer recall, while higher diving qualification was associated with better recall. Performance on the surface was a good predictor of performance at depth. Qualitative analysis rendered three themes, namely focus vs. distraction, following instructions, and shape memory. Psychometric properties of the subjective narcosis measure were also reported.

Theoretical implications include support for the slowed information processing model when completing complex neuropsychological tasks, as well as support for the memory model, thus suggesting that this particular pattern of memory impairment occurs because encoding under narcosis produces a weaker memory trace than normal.

Lastly, the study has a number of implications for industry. For example, divers need to compensate for slowed task completion by, firstly, planning more time to complete complex tasks, and secondly, by practicing those tasks prior to the actual deep dive (either on the surface or in shallow water). The need for using additional forms of recording of events or objects at depth, to aid memory encoding and subsequent recall at surface was also emphasised.

OPSOMMING

Kommersieële en militêre duik vind dikwels plaas in ‘n omgewing met swak sig, waar duikers moet staatmaak op taktiele sintuie, eerder as op visuele sintuie.

Die tesis begin met ‘n oorsig oor die huidige kennis rakende neurosielkundige verskynsels van stikstof narkose, en het ‘n aantal tekortkominge gevind. Meer spesifiek, die menslike faktor in die effek van hiperbariese druk op taktiese persepsie en geheue is nog nie sistematies bestudeer nie. Dit is verder nie duidelik presies hoe sielkundige faktore (angs, gemoedstoestande) en demografiese faktore (ouderdom, opvoeding, tegniese blootstelling, ondervinding) taktiele persepsie en geheue onder toestande van hiperbariese druk sou beïnvloed nie. The korrelasie tussen die subjektiewe ervaring van narkose, taktiele taakverigting, en sielkundige en biografiese veranderlikes is ook nie bekend nie. Die studie het verskeie neurosielkundige aspekte van stikstof narkose, met spesifieke verwysing na taktiele persepsie en geheue, sowel as die verhouding tussen taktiele prestasie en sielkundige en biografiese faktore ondersoek.

Die effek van hiperbariese druk op taktiele persepsie en geheue is ondersoek deur hierdie funksies te toets by 6 en 1 ATA, deur middel van ‘n oorkruis studie ontwerp, waar twee groepe die take voltooi het, in teenoorgestelde volgorde. Die sielkundige veranderlikes het bestaan uit trek-angs, tydelike gemoedstoestande, en die subjektiewe evaluering van narkose, terwyl die biografiese veranderlikes ouderdom, opvoeding, en vorige tegniese blootstelling ingesluit het.

Die resultate het die nadelige effek van stikstof narkose op taktiele vorm persepsie en manipulasie gedemonstreer, ongeag die rigting van toetsing. Dit het ook hierdie effek op taktiele vorm geheue gedemonstreer, hoewel die rigting van toetsing wel hier ‘n rol gespeel het.

Hoër trek-angs was geassosieër met swakker herroeping, en spanning met ‘n groter agteruitgang in herroeping, terwyl matheid geassosieer was met swakker taakvoltooiing. Subjektiewe ervarings het ook ‘n rol gespeel, met ervarings van fisiese spanning (verhoogde opwekking) geassosieer met beter herroeping, en ervarings van kognitiewe onderdrukking (verlaagde opwekking) met groter agteruitgang in herroeping. Laer akademiese kwalifikasie was geassosieer met swakker herroeping, terwyl hoër duik kwalifikasie geassosieer was met beter herroeping. Taakverrigting op die oppervlak was ‘n goeie voorspeller van prestasie op diepte. Kwalitatiewe analiese het drie temas geidentifiseer, naamlik fokus vs. afleibaarheid, die volg van instruksies, en vorm geheue. Die psigometriese eienskappe van die subjektiewe narkose meetinstrument is ook gerapporteer.

Teoretiese implikasies van die studie sluit in ondersteuning vir die vertraagde prosesseringsmodel, wanneer komplekse neurosielkundige take voltooi word, sowel as ondersteuning vir die model vir hierdie spesifieke herroepingspatroon wat ‘n swakker geheuespoor laat wanneer enkodering plaasvind onder toestande van narkose.

Die studie het ook praktiese implikasies vir industrie. Dit is byvoorbeeld nodig om te kompenseer vir vertraagde taakvoltooïng deur, eerstens, die beplanning vir meer tyd om komplekse take te voltooi, en tweedens, deur daardie take te oefen voor die diep duik plaasvind. Die noodsaaklikheid vir additionele maniere om gebeure of voorwerpe op diepte vas te lê is ook beklemtoon.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ATA	atmosphere absolute
BQ	Biographical Questionnaire
BRUMS	Brunel Mood State
CNS	central nervous system
EHE	experimental hyperbaric exposure
fsw	feet sea water (unit)
GABA	gamma-amino butyric acid
GP	Grooved Pegboard
HPNS	High pressure nervous syndrome
IGN	inert gas narcosis
kPa	kilopascal (unit)
LTM	long-term memory
MRA	Multiple Regression Analysis
msw	metres sea water
NN	nitrogen narcosis
PICF	Participant Information and Consent Form
POMS	Profile of Mood Scales
SHAS	Subjective High Assessment Scale
STAI	State-Trait Anxiety Inventory
STPI	State-Trait Personality Inventory, Trait Anxiety
TMD	total mood distress
TNT	Tupperware Neuropsychological Task
WAIS-R	Wechsler Adult Intelligence Scale – Revised
WMS-R	Wechsler Memory Scale – Revised

CHAPTER 1: INTRODUCTION

The effects of deep diving on human performance have been subject to serious scientific investigation for almost two centuries. The effects of working underwater and in greater depth, and with more technologically advanced equipment and material, is increasingly better understood. However, within this field of study, human performance through the tactile modality is a neglected area of research.

The commercial and military deep diving environment is typically a low visibility environment, where dependence on visual senses often needs to be replaced by a reliance on tactile senses. The purpose of this study is to investigate certain neuropsychological aspects of nitrogen narcosis (NN), with special reference to tactile perception and memory, and to examine the relationships of tactile performance with other psychological and biographical factors.

The effects of experimental hyperbaric exposure (EHE) on tactile performance (referring to form perception, mental manipulation and fine motor coordination), and tactile memory (referring to shape memory) were examined through testing of these functions at 6 ATA[1] and 1 ATA, using a cross-over design.

The psychological variables include trait anxiety, transient mood states, and subjective ratings of narcosis, while the biographical variables include age, education, and previous technical exposure.

Chapter 2 will present a review of the available literature, which will culminate in a formulation of the specific objectives of the study in Chapter 3. Chapter 4 will describe the methodologies employed to achieve these objectives. The findings will be reported in Chapter 5, and Chapter 6 will discuss these results, before concluding with some of the lessons that can be learnt from this study.

[1] Both the commercial diving industry and the diving medical scientific community use atmospheres absolute (ATA) as their benchmark standard. 1 ATA equals 101.325 kPa, and 6 ATA is equal to 607.95 kPa

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

This chapter will review the available literature on neuropsychological performance in hyperbaric environments. The first section (Section 2.2) will provide an overview of inert gas narcosis (IGN), with specific reference to the effects of NN on human behaviour. As this study is primarily interested in tactile functions, e.g. in form perception, fine motor manipulation of shapes, and tactile shape memory, specific emphasis will be placed on understanding the underlying psychological principles that regulate such information processing. A number of other factors – both in terms of personal and environmental variables – are further implicated in affecting human performance under water and at depth, and these will be reviewed in Section 2.3. Section 2.4 will briefly review a number of relevant psychological constructs, with specific reference to anxiety, while Section 2.5 will introduce tactile perception. Section 2.6 will summarise the salient findings, to be followed by the problem statement in Section 2.7.

2.2. Inert gas narcosis

2.2.1 Definition and description

Inert gas narcosis (IGN) refers to the effects of breathing inert gases at pressures higher than 1 atmosphere absolute (ATA) (Bennett, 1993). In the broadest sense, the term 'narcosis' refers to the reversible depression of function of an organism (Fowler, Ackles & Porlier, 1985). Nitrogen is the most common inert gas found in air, and narcosis is most commonly found in compressed air diving. Nitrogen narcosis thus describes a group of symptoms characterised by deteriorating cognitive and neuromuscular functions, and disturbed mood and behaviour (Petri, 2003). For this reason, NN may have a negative impact on underwater work performance and can be a factor in dive-related accidents (cf. Kneller, Higham & Hobbs, 2012).

The threshold for the occurrence of nitrogen narcosis is usually regarded to be at a depth of about 30 metres of seawater (4 ATA) during compressed air breathing (Bennett, 2004), with the signs and symptoms becoming increasingly pronounced, as depth increases (Bennett, 2004). At depths greater than 6.5 ATA, human performance deteriorates significantly, and at depths greater than 10 ATA, signs and symptoms are severe, with the possibility of a diver becoming unconscious (Bennett, 2004).

The general or average threshold depth of 30msw has been established by objective measurements of performance decrements. Subjective reporting of depth of onset of symptoms varies widely, however, it is strongly influenced by suggestibility. Recently, computerised measures that are more sensitive have found some indications that psychomotor function may be impaired between 10 and 30msw in a laboratory setting (Petri, 2003). It is not clear whether these impairments have practical implications for real dives.

The signs and symptoms are similar to those seen in alcohol intoxication and the early stages of hypoxia and anaesthesia, with an equally wide variation in susceptibility (Bennett, 2004, p 226). The issue of individual susceptibility is discussed in more detail under Section 2.5 General Findings. It is particularly the euphoria, light-headedness, and motor incoordination of narcosis that has been likened to alcohol intoxication (Lowry, 2002). There is evidence of a significant correlation between alcohol and NN (at 5–6 ATA, breathing air) on both subjective and behavioural measures, which suggest that a biological factor may account for the variations in intensity experienced among individuals (Hobbs, 2008; Monteiro, Hernandez, Figlie, Takahashi & Korukian, 1996). Interestingly, it appears that the degree to which an individual's performance is impaired by alcohol can predict the degree of impairment when narcotic (Hobbs, 2008).

Studies into the metacognition of divers showed the inaccurate nature of subjective judgements in their own abilities while experiencing narcosis (Harding, Bryson & Perfect, 2004). Metacognition refers to the level of awareness of cognitive functioning, with the implication that, if individuals can sense their own level of cognitive performance accurately (as well as a decrease in performance), then they can react appropriately to that situation. For example, Mount & Milner (cited in Harding et al., 2004) told divers to expect narcosis at different depths, and that is exactly what divers reported during their dives. The implications were that divers were not aware of the true level of their impairment, and in fact, that they tended to over-estimate their ability because of incorrect self-beliefs that they did not suffer from narcosis, despite evidence to the contrary. Harding et al. (2004) found that divers believed their performance at 5 ATA was equal to their performance at 1 ATA on reaction time tasks, and better on a long-term memory task at 5 ATA than at 1 ATA, even when the actual outcome was poorer. They further report that a cohort of divers reported symptoms of narcosis to start at depth deeper than would normally be expected, indicating a possible denial of symptoms, or at least a lack of awareness of symptoms.

2.2.2. Other inert gases besides nitrogen

The same signs and symptoms of NN, or breathing air at more than 4 ATA, have also been observed with other metabolically inactive gases, e.g. neon, argon, krypton, xenon, hydrogen, and the anaesthetic gases, although at different partial pressures (Fowler et al., 1985; Lowry, 2002). The use of different gas mixtures require the use of advanced technology and training, and is usually used for diving at increased depth or duration. The present study is concerned with the effects of narcosis when breathing normal air (i.e. surface mixture) under specific pressures (i.e. 6 ATA), within limited decompression schedules. However, a quick overview of other gases is provided for the sake of comprehensiveness (from Bennett, 1993).

Helium does not lead to narcosis, and is thus used for deep and saturation diving. It has a number of disadvantages, e.g. voice distortion, high thermal conductivity, and cost. It further is associated with High Pressure Nervous Syndrome (HPNS) (at depths of 150m+), although the association may not be an effect of helium, but rather due to the extreme depth, which also requires the use of this gas to reach it. HPNS must be distinguished from IGN (Section 2.2.7). Neon does not lead to narcosis either, but is denser than helium, and less often used due to its possible adverse respiratory effects, i.e. increased work breathing relative to hydrogen. Hydrogen is less narcotic than nitrogen, but dangerous as it becomes explosive in mixtures of more than 4% oxygen. The addition of hydrogen to heliox delays to greater depths the signs and symptoms of HPNS. Argon is 2 to 4 times more narcotic than nitrogen. Xenon too has a much greater narcotic effect than nitrogen, and produces anaesthesia in humans at depths of 10m. Krypton and nitrous oxide are both very narcotic.

2.2.3. Human performance models

A historical overview of the developments around the scientific understanding of IGN can be found in Bennett (1993, 2004) and Lowry (2002). The aetiology of IGN lies in the realm of biophysiology and biochemistry, and is beyond the scope of this thesis. A number of hypotheses have been investigated in the literature, including the lipid solubility hypothesis, the critical volume concept, and the multi-site expansion model. Brief reviews can be found in Bennett (1993) and Lowry (2002), and more recently in Smith & Spiess (2010) and Rostain, Lavoute, Risso, Vallée & Weiss (2011).

The site of action of narcosis in the brain probably lies at the synapses. Mechanisms involving interference with the electrochemical mechanisms necessary for the transfer of electrical potential across synaptic gaps is thought to contribute to narcosis (Bennett, 2004). Polysynaptic regions of the brain, such as the ascending reticular formation system and the cortical mantle, are likely to be regions of the brain most affected (Bennett, 2004). Studies have investigated inhibitory and excitatory neurotransmitters and receptors in the central nervous system (CNS), including noradrenaline, serotonin, dopamine, gamma-amino butyric acid (GABA) and glycine (Lowry, 2002). Exposure of rats to narcosis raised extra-cellular dopamine in the brain areas controlling the extra-pyramidal system, which may account for some of the neuromuscular disturbances of IGN (Barthelemy-Requin, Semelin & Risso, 1994).

A number of human performance models for IGN have been formulated (cf. Fowler et al., 1985, for an earlier review), including the descriptive model, the hierarchical organisation model, the operant paradigm, and the slowed processing model.

The descriptive model defines NN as a set of signs and symptoms, and identified performance decrements at increased pressure for, among other things, arithmetic (Bennett, 1993; Mears & Cleary, 1980), long-term memory (Fowler, 1973; Philp, Fields, Roberts, 1989; Tetzlaff, Leplow, Deistler, Ramm, Fehm-Wolfsdorf, Warninghoff & Bettinghausen, 1998; Vaernes & Darragh, 1982), reaction time (Bennett, 1993), and motor dexterity (Bennett, 1993; Mears & Cleary, 1980) functions. Motor performance seem more resilient to the effects of narcosis than cognitive functions (Abraini, 1997; Abraini & Joulia, 1992). This conceptualisation has practical value, as accurate prediction of performance will lead to better preparation to avoid or manage these impairments. However, it has limited value for theoretical conceptualisations.

The hierarchical organisation hypothesis posits that 'higher' physiological centres are more sensitive to anaesthetics, and that they will be affected first. This implies that the more complex mental functions should be affected more quickly by narcosis than the less complex functions. This model has limited explanatory power (Fowler et al., 1985).

The operant paradigm draws on the classical theories of behaviourism, and it was developed for use in animal studies on the effects of narcosis. This allowed for studies on the comparative effects of inert gases, and their progressive effects at greater pressures. There are suggestions that results with this technique can be generalised to humans, making it a useful avenue for future study (Fowler et al., 1985).

A more sophisticated approach explains narcosis through the slowed information processing model (cf. Fowler et al., 1985 for an earlier review). The effect of narcosis is thus ascribed to a single underlying functional effect: slowing due to decreased arousal. This is manifested by an increase in response time, and often by a decrease in accuracy. To understand how narcosis disrupts complex tasks, one needs to regard the information processing system as being dynamic and as involving factors such as cumulative slowing in working memory and alterations in strategy. The following discussion, unless otherwise indicated, is adapted from Fowler et al. (1985, p.377–387).

A simplified version of the information processing system is illustrated in Figure 2.1.

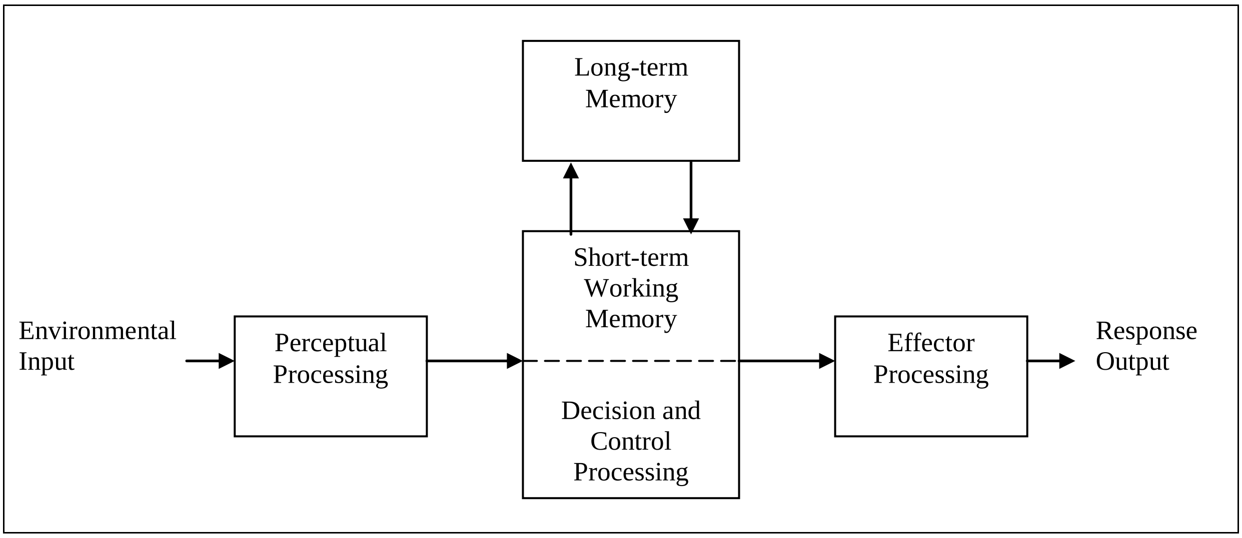

Figure 2.1: Effects of exposure to compressed air (Fowler et al., 1985).

The information processing system has three main features:

The **first** is a series of stages, each of which takes time to process information. These stages are referred to as *structural* variables and are named after the kind of processing they perform – perceptual, stimulus-response, and effector stages. Other kinds of structural variables are memory stores, which hold information either temporarily or permanently. Each stage takes time to process information and adds an increment to the total time required for a response.

The **second** feature is that overall efficiency is determined by the level of arousal or activation – called a *functional* variable. Up to a certain point, an increase in arousal improves performance (Dodge-Yerkson law), where after it interferes with optimal performance. An important role assigned to the ascending reticular activating system is regulating cortical excitability.

The **third** feature encompasses *strategic* variables, and consists of control processes, which organise the resources of the system to accomplish a particular task. These processes give the systems its complex dynamic characteristics and may or may not be under the conscious control of the performer. They include the distribution of attention, decision criteria, rehearsal strategies, and speed-accuracy trade-off settings (e.g. how performers strike a balance between speed and accuracy). The strategy used to perform a task is likely to change under narcosis, but is secondary to slowing, i.e. as a compensatory response to slowing or in reaction to euphoria.

Narcotic performance deficits, reflected in decreases in the speed or accuracy of responses, could be due to structural, functional, or strategic variables, either alone or in combination.

Evidence indicates that slowing due to narcosis is not caused by a disruption of processing stages (i.e. it is not caused by structural deficiency), but by a decrease in the efficiency of the system as a whole (i.e. functional changes). Support for this came from studies on the additive effect of alcohol (a CNS depressant) on slowing (Hamilton, Fowler & Porlier, 1989), and the ameliorative effect of amphetamine (a CNS excitant) on slowing (i.e. less slowing) (Hamilton at al., 1989). Further, under conditions of narcosis, time is judged to pass more quickly, which may imply a slowing down of an 'internal clock' (i.e. a functional slowing of the CNS).

There is further tentative support that a decrease in accuracy may be due to a strategic rather than structural change – in other words, due to a shift in speed-accuracy trade-off setting rather than a distortion in information transmission. Two reasons for this have been proposed: Firstly, divers distribute the impact of narcosis between speed and accuracy so the loss of speed is not so noticeable, and secondly, the euphoria induced by narcosis makes divers less reluctant to maintain a particular setting. Thus, task completion strategies may change under conditions of narcosis, but such changes are secondary to slowing, i.e. they appear as compensatory responses to slowing or in reaction to euphoria (Fowler, Hendriks & Porlier, 1987; Fowler, Mitchell, Bhatia & Porlier, 1989).

The role of working memory may be critical in understanding the effect of narcosis on complex tasks. It has been hypothesised that working memory processing occurs in a series of operations (Baddeley & Hitch, 1994). If each operation performed is slowed by narcosis, then due to the iterative nature of processing, there will be cumulative slowing. Response time will increase, as the total number of operations that must be performed increases. Support for this hypothesis came from studies involving complex tasks, like arithmetic. This perspective may also provide an explanation of why psychomotor tasks are less sensitive to narcosis than are cognitive or response time functions – dexterity requires fewer mental operations (thus leading to less cumulative slowing).

Subjective symptoms of narcosis (e.g. euphoria, state of consciousness, inhibitory state) may further influence performance, for example, by causing shifts in the value of strategic variables (e.g. a lack of caution may mean that accuracy is allowed to deteriorate), by distracting attention, and by creating anxiety, which in itself can degrade performance.

Currently, there is good provisional evidence in support of the slowed information processing model (Hamilton et al., 1989), and previous weaknesses of the theory in explaining memory loss (Lowry, 2002) have recently been adequately addressed (Hobbs & Kneller, 2009).

Measurement of all these models is complicated by a tri-factor interaction, where the roles of anxiety and apprehension, water effects, and inert gas pressure all contaminate the results in various ways.

For example, anxiety in itself impairs performance, even at the surface. The water effect refers to the limitations a diver faces when entering the underwater environment, even at shallow depths, due to the issues of movement in water, the use of life-support equipment, and so forth (Weltman, Christianson & Egstrom, 1970), all which need to be isolated from the actual effect of inert gas (narcosis). The water effect is discussed in more detail in Section 2.3.1, and anxiety in Section 2.4.1.

2.2.4. Creating context to review specific findings

The findings from available studies (which will be discussed in Sections 2.2.5 and 2.2.6) need to be interpreted cautiously. It is difficult to study the effects of narcosis systematically, due to the many variables that need to be controlled, and the costs that are involved in large sample studies.

Due to high costs, studies conducted used limited numbers of dives, and/or used working dives to collect their data, where less experimental manipulation was possible. For the same reasons, sample sizes are generally small (cf. Weybrew, 1978, for an older review on sample sizes).

Some of the variables that confound comparisons between studies include:

1) The technical aspects of experimental conditions, e.g. gas mixtures, gas partial pressures, temperature, and rates of compression;
2) The demographic backgrounds of test subjects, e.g. type (professional vs. sport divers vs. non-divers), age of participants, their training and exposure, and motivation to participate;
3) Environmental conditions, e.g. wet vs. dry (Baddeley, 1966; Baddeley, DeFigueredo, Hawkswell-Curtis & Williams, 1968; Baddeley & Flemming, 1967; Baddeley & Idzikowski, 1985), the use of protective clothing, and the other potentiating factors discussed in the next section;
4) Different measurements (tests and indicators) are used under different definitions of neuropsychological functions. This makes it difficult, at times, to untangle the underlying construct that the outcomes are supposed to measure. The use of self-reports, particularly in older studies, further complicates the issue.

There are also different methods for reporting results. Some investigators report decrements in performance in terms of percentages, which can be related to either normobaric performance scores or the scores of control groups. Others use standard deviations from the mean, which are in turn influenced by the level of interpersonal heterogeneity, which varies across samples and traits. Others still present graphs or charts only.

Apart from the fact that different studies used different participants and different measurements, and did so under different conditions, inter-individual susceptibility to narcosis further confounds the issue, as different people react differently to narcosis, and are affected by it at different depths. Perhaps because of this, neuropsychological research into the cognitive effects of NN is plagued by inconclusive and sometimes contradictory results.

2.2.5. General findings

Before reviewing the specific neuropsychological effects of narcosis on human behaviour, general findings regarding narcosis and performance will be dealt with, to create a background against which the succeeding section can be interpreted.

The most severe signs and symptoms of narcosis are present immediately when reaching the desired pressure (Bennett, 1993), with narcosis usually more severe immediately on arrival at the specific depth. There may be some improvement shortly afterwards, followed by a stabilising in the level or degree of narcosis (Bennett, 2004). Further ‘improvements’ are likely to be primarily subjective improvements (i.e. some form of mental compensation), as objective tests show no change (see discussion of adaptation that follows later). Signs and symptoms of narcosis are not affected by the duration of exposure.

The signs and symptoms become more marked with greater depth (Bennett, 1993). On decompression, recovery is rapid, with no after-effects, except an occasional amnesia to events while at depth (i.e. during the narcotic state) (Bennett, 2004). Very rapid compression appears to potentiate narcosis (Bennett, 2004). The extent of performance decrement appears directly proportional to task complexity (Kiessling & Maag, 1962).

There is great variation in individual susceptibility to narcosis and the severity of its effects. As mentioned, the threshold for the objective identification of narcotic effects is 30msw. The experience of NN is further highly subjective. One study found that reports of subjective onset of narcosis on average come at 34.5m, with a range of 15 to 60 m (Harding et al., 2004).

The effect of narcosis on performance is greater under wet than dry conditions (Baddeley, 1966; Baddeley & Flemming, 1967; Baddeley & Idzikowski, 1985). Thus, results from dry chambers cannot always be transferred directly to wet conditions. Inside a hyperbaric chamber, the psychological stressors of ocean diving are absent, as are the muscular strain and environmental conditions (buoyancy, temperature) encountered there (De Moja, Reitano & De Marco, 1987). In the same way, results from protected environments (e.g. wet tank) cannot always be transferred directly to open-water conditions (Baddeley et al., 1968; Baddeley & Idzikowski, 1985). Open water also elicits performance interference from the water effect, as well as potential dangers (i.e. anxiety). It is generally accepted that the greater effect of NN in the open water, relative to hyperbaric chambers, can largely be attributed to increased anxiety (Hobbs & Kneller, 2011).

There is no evidence that age or formal education play any significant role in moderating the effect of hyperbaric pressure, although it has been suggested that greater intellectual ability protects divers to some extent against the effects of narcosis (Bennett, 1993). There is further no evidence that previous technical exposure (whether formal training or informal contact) play a role in moderating the effects of NN, although it can be hypothesised that formal exposure, through a process of over-learning of principles or practices, may protect against impaired performance on tasks requiring technical reasoning or manual dexterity.

A number of diver characteristics have been found to potentiate or moderate the severity of narcosis: More experienced divers appear to be less affected (Bennett, 1993; De Moja et al., 1987), but as with intellectual ability, there are large differences in the range of individual responses (Behnke, 1984). Apprehension and anxiety (Davis, Osborne, Baddeley & Graham, 1972) exacerbate the effects of narcosis, especially the impairment of psychomotor dexterity (Baddeley & Idzikowski, 1985; Kneller et al., 2012; Mears & Cleary, 1980). The dangers of a hostile environment may further potentiate the effects of narcosis (Baddeley et al., 1968; Baddeley, 1972). Anxiety is discussed in more detail in Section 2.4.1.

A number of physiological and chemical characteristics have also been found to potentiate the severity of narcosis: Any increases in exogenous or endogenous carbon dioxide potentiate narcosis synergistically (Bennett, 2004; Fothergill, Hedges & Morrison, 1991). Thus it is likely to be more severe in the swimming or working diver wearing a breathing apparatus than in the case of a diver in a pressure chamber (Bennett, 2004). Variations in the oxygen percentage in breathing mixtures further affect the degree of narcosis (Bennett, 2004; Frankenhaeuser, Graff-Lonnevig & Hesser, 1963). Hard work and/or fatigue (Bennett, 1993) facilitate the effects of narcosis, although this might be through the mechanisms of hypercapnia or carbon dioxide retention referred to above. Moderate work or exercise may conversely ameliorate the effects of narcosis due to its role in arousing the CNS (cf. Fowler et al., 1985). No gender effect of NN on neuropsychological performance has been found (Jakovljevic, Vidmar & Mekjavic, 2012).

Ethanol consumption depresses the CNS, and exacerbates the effects of narcosis (Fowler et al., 1987; Hamilton et al., 1989). As mentioned, individuals with greater sensitivity to alcohol also display a greater sensitivity to narcosis. In contrast, amphetamine excites the CNS, and ameliorates the effects of narcosis (Fowler et al., 1985; Hamilton et al., 1989); however, its effects may be unpredictable (Lowry, 2002). The effects of ethanol and amphetamines are both in line with the view that narcosis depresses the CNS. The effects of different pharmaceutical preparations are reviewed in Bennett (1993). Some protect against narcosis, while others enhance it. There are indications that lithium carbonate may ameliorate the effects of narcosis (Leach, Morris & Johnson, 1988).

Findings regarding adaptation to the effects of NN are generally inconsistent (Fowler et al., 1985). Some studies suggest that frequent exposure may afford some adaptation (Bennett, 1993; Moeller & Chattin, 1975), although continuous exposure may only lead to adaptation after a number of days – 8 or 9 in one study (Coler, Patton & Lampkin, 1971). Acclimatisation is probably a more accurate description, rather than adaptation, as most other studies found little or no behavioural adaptation to NN in response to short repetitive hyperbaric exposures (Hamilton, Laliberté & Fowler, 1995; Moeller, Chattin, Rogers, Laxar & Ryack, 1981; Rogers & Moeller, 1989; Whitaker & Findley, 1977). Subjective adaptation can occur without parallel performance improvement (Hamilton, Laliberté & Heslegrave, 1992), and the anecdotal reports of adaptation by divers can probably be attributed to the subjective rather than the behavioural components of narcosis (Hamilton et al., 1992).

Improvements in performance are generally attributed to non-specific learning, and the adaptation of subjective symptoms is often mistaken for performance adaptation (Hamilton et al., 1995). The importance of non-specific learning to lessen the effects of narcosis emphasise the value of practice and over-learning of behaviour, prior to underwater work.

2.2.6. Clinical manifestations

Attempts to quantify the effects of IGN can be roughly divided into two methods (Lowry, 2002): measuring the behavioural expression on neuropsychological tasks, and observing changes in neurophysiological parameters. The latter lies outside the scope of this thesis and only the neuropsychological ('behavioural') expressions of NN will be reviewed here.

It is not always clear how to organise behavioural findings, partly due to methodological issues raised previously, but also because the tests, tasks and measurements used at times cover multiple neuropsychological domains. For descriptive purposes, the clinical manifestations will be organised into three major groups, namely cognitive performance, psychomotor functioning, and mood states and social behaviour. An effort has been made to classify the results of measures according to the major functional activity that they elicit, but it is conceded that, while the allocation presented here tried to follow convention, it was not always possible, and some were assigned slightly arbitrarily.

In general terms, narcosis has been defined as a slowing in mental activity, with delays in auditory and olfactory stimuli and a tendency to word-idea fixation. The resulting limitation in power of association and perception then becomes dangerous in the presence of overconfidence associated with NN (Bennett, 2004). It is possible to view mental slowing as an – or even the – underlying factor affecting all of the neuropsychological functions below, but for the sake of organisation, reaction time will here be included under cognitive functions.

Generally, higher functions, such as reasoning, judgement, recent memory, learning, concentration and attention are affected first. If the partial pressure of inert gas is further elevated, it results in a progressive deterioration of psychomotor functioning and mental performance, and an increase in automatisms, idea fixation, hallucinations, and culminating finally in stupor and coma (Lowry, 2002). Perceptual narrowing can occur, where divers may become less aware of potentially significant stimuli outside their prescribed task (Lowry, 2002).
A summary of the behaviour characteristics of NN according to depth can be found in Table 2.1 (from Edmonds, Lowry, Pennefather & Walker, 2002, p 186).

Table 2.1: Effects of exposure to compressed air at increased pressure and depth.

Pressure (ATA)	**Effects**
2–4	Mild impairment of performance on unpractised tasks
	Mild Euphoria
4	Reasoning and immediate memory affected more than motor coordination
	and choice reactions
	Delayed response to visual and auditory stimuli
4–6	Laughter and loquacity may be overcome by self-control
	Idea fixation, perceptual narrowing, and over-confidence
	Calculation errors; memory impairment
6	Sleepiness; illusions; impaired judgement
6–8	Convivial group atmosphere; may be terror reaction in some; talkative;
	Dizziness reported occasionally
	Uncontrolled laughter approaching hysteria in some
8	Severe impairment of intellectual performance
	Manual dexterity less affected
8–10	Gross delay in response to stimuli
	Diminished concentration; mental confusion
10	Stupefaction
	Severe impairment of practical activity and judgement
	Mental abnormalities and memory deficits
	Deterioration in handwriting; uncontrollable euphoria; hyperexcitability;
	Almost total loss of intellectual and perceptive faculties
>10	Hallucinogenic experiences
	Unconsciousness

From Edmonds et al., 2002, p 186

Cognitive performance

Cognitive functions are affected by narcosis to a greater extent than neuromuscular functions.

Attention and concentration

Choice reaction time is consistently impaired under narcosis, indicating a slower processing of information under pressure (Bennett, 1993; Fowler et al., 1989). In general, more time is needed to complete tasks. Table 2.2 presents a sample of the choice reaction time studies done to date.

Concentration, as measured by a modified Stroop Test at 6 ATA breathing air, showed an 11% decrement in scores (Fothergill et al., 1991). Digit-symbol substitution (WAIS-R) at 30 m (4 ATA) breathing air did not show any difference from a control group (Gallway, Millington, Wolcot, Mirsky, Van Gorp & Wilmeth, 1990), although the depth may not have been enough to elicit measurable effects.

Visual scanning seems particularly sensitive to the effect of cumulative depth. One study found that performance on the Trailmaking Test (A&B) at 4 ATA, breathing air, did not differ from a control group (Gallway et al., 1990). The same test administered at 7 ATA, breathing air, found significant impairment (Van Wijk, 2008a). Other studies also reported decrements in visual scanning performance at 7 ATA (Moeller et al., 1981; Whitaker & Findley, 1977), although the extent of the decrement was not reported. Table 2.3 presents a sample of the visual scanning studies done to date. It was hypothesised that the pressure at 4 ATA may not have been enough to elicit clear decrements in performance, and that the impairment of performance at 7 ATA could then be attributed to the observation that increased pressure increases the impairment of cognitive functions (Bennett, 1993).

Time estimation is consistently affected, with divers giving significantly longer time estimations under pressure. There are suggestions that this may possibly be due to the water effect as much as to narcosis (Mears & Cleary, 1980), or that it may refer to the slowing of the internal clock (Fowler et al., 1985). Table 2.4 presents a sample of the time estimation studies done to date.

In general, greater depth is associated with greater distractibility (Edmonds et al., 2002).

Table 2.2: Studies investigating choice reaction time.

Conditions		Outcome	Source
Pressure	**Breathing gas**		
100 fsw (±4 ATA)	Air	21% decrement in response time	Kiessling & Maag, 1962
188 fsw (±7 ATA)	Air	Significant slowing in response latency	Whitaker & Findley, 1977
6 ATA	Air	No effect	Abraini & Joulia, 1992
7 ATA	Air	Small but significant decrement of 5%	Abraini & Joulia, 1992

Table 2.3: Studies investigating visual scanning and tracking.

Conditions		Outcome	Source
Pressure	**Breathing gas**		
30msw (4 ATA)	Air	No effect	Gallway et al., 1990
188fsw (±7 ATA)	Air	Significant impairment in pursuit tracking task	Whitaker & Findley, 1977
7 ATA	Unknown	Decrement in visual scanning performance	Moeller et al., 1981
7 ATA	Air	Trail A: 46% decrement Trail B: 54% decrement (completion time)	Van Wijk, 2008a

Table 2.4: Studies investigating time estimation.

Conditions		Outcome	Source
Pressure	**Breathing gas**		
106fsw (±3.5 ATA)	Normoxic-nitrogen mixture	Significantly longer time estimations	Miller, Bachrach & Walsh, 1976
30msw (4 ATA)	Air	Significantly longer time estimations	Mears & Cleary, 1980
122msw (±13 ATA)	Unknown	Disorganised sense of time	Adolfson, cited in Bennett, 1993

<u>Language</u>

It is not clear to what extent verbal comprehension is affected under pressure. Divers can recognise language as communication, and the ability to comprehend instructions is intact to great depth. At 13 ATA, orders are appreciated but ignored (Adolfson, cited in Bennett, 1993). This is probably because the euphoria interferes with task execution, rather than it suggesting a language deficit.

Memory

No previous studies with hyperbaric pressure and tactile memory could be located.

The impairment of verbal memory (as assessed by word lists) has been well documented (cf. Hobbs & Kneller, 2009; Tetzlaff et al., 1998), especially the storage of information in long-term memory (LTM). Short-term memory does not seem to be affected by narcosis to the same degree (Fowler, 1973; Fowler et al., 1987; Morrison & Zander, 2008; Philp et al., 1989). Verbal memory, encoded under conditions of hyperbaric pressure, is impaired when free recall is tested under both hyperbaric and normobaric conditions (Hobbs & Kneller, 2009; Vaernes, 1982; Vaernes & Darragh, 1982; Tetzlaff et al., 1998). It has been suggested that the effects of narcosis on memory could be explained by a disruption of the processing that is required to both encode information into long-term memory and to retrieve it (Tetzlaff et al., 1998). A biological factor might also be implicated, as a reduction in recall capacity under conditions of narcosis is associated with both prolactin and testosterone levels (Vaernes & Darragh, 1982).

However, cued recall appears to correct the deficit in free recall (Fowler, White, Wright & Ackles, 1980; Gallway et al., 1990; Hobbs & Kneller, 2009; Philp et al., 1989; Tetzlaff et al., 1998). Cueing refers to the process enacted by an individual to retrieve information through the use of external memory cues (Hobbs & Kneller, 2009). In other words, hyperbaric pressure seems to have less effect on memory recognition than free recall. This suggests that information is stored in LTM (i.e. the process of encoding is not disrupted), but that retrieval of learnt information (under narcosis) is impaired.

Then again, as recall at surface after a dive (of material learned under narcosis) is also affected, an impairment of self-guided search is an inadequate explanation of the effect of narcosis on memory. A recent hypothesis (Hobbs & Kneller, 2009) postulates that the pattern of impairment reported occurs because encoding under narcosis produces a weaker memory trace than normal. According to the information processing model, narcosis disrupts processing when learned material is encoded (Fowler et al., 1985), resulting in fewer cognitive resources being available for encoding. Thus the material is learned, but the quality of encoding and processing is reduced, producing a weaker memory trace. Hobbs & Kneller (2009) provide some theoretical support for this. In comparison, when possible responses ('cues') in a recognition task are provided, a less 'sophisticated' level of processing is required. This explanation would explain why material learned under narcosis would be harder to recall than material learned in shallow water, regardless of whether the act of recall took place in shallow or deep water.

This is supported by findings that, in general, over-learned tasks are not affected, but new learning is negatively affected by narcosis (Fowler et al., 1987; Vaernes, 1982; Vaernes & Darragh, 1982), possibly because over-learned tasks were originally encoded under normobaric conditions. Further support comes from a study that found that rehearsal strategies changed under narcosis. It was hypothesised that the reduction in efficiency of encoding could be caused by the slowing of information processing, in that fewer words are rehearsed as a strategy to encode the remaining words more effectively (i.e. if there is slower processing, then there is a need to compensate for this loss of efficiency – by rehearsing fewer words) (Fowler et al., 1987).

Current evidence indicates that memory decrements in hyperbaric chambers are comparable to those underwater (Hobbs & Kneller, 2009). Cueing is thus of practical value, as it may be an important strategy for eliciting information acquired during exposure to narcosis (Philp et al., 1989). Free recall from the primacy[2] regions is most impaired by hyperbaric pressure, with little effect on free recall from the recency region (Fields, 1986, cited in Fowler et al., 1987; Philp et al., 1989). Recall of earlier information may thus be at particular risk if encoded under narcosis.

Verbal memory, if assessed through logical memory (using the WMS-R) and learned at 4 ATA, shows no impairment (Gallway et al., 1990). Logical memory has a cued component, which might explain the negative finding. Table 2.5 presents a sample of the verbal memory studies done to date.

Table 2.5: Some studies investigating verbal memory.

Conditions		**Outcome**	**Source**
Pressure	**Breathing gas**		
36msw (±4.5 ATA)	Air	20% decrement in immediate recall from primacy regions	Philp et al., 1989
		50% decrement in delayed recall	
		recognition unaffected	
50 msw (6 ATA)	Air	recall of material learned at surface not affected when recalled at depth	Tetzlaff et al., 1998
		significant impairment of recall at depth of material learned under narcosis	
		significant impairment of recall at surface of material learned under narcosis	
		Recognition not significantly affected	

[2] Primacy refers to the earliest stimuli presented in a series and recency to the last

40 msw (5 ATA)	Air	10% loss at immediate recall	Morrison & Zander, 2008
		18% loss after 5 min recall	
		39% loss after 2 hour delay (22% loss of basic info, 51% loss of abstract info)	
37–40 msw (±5 ATA)		Free recall of material learned at surface not affected when recalled at depth	Hobbs & Kneller, 2009
		Significant impairment of recall at depth of material learned under narcosis	
		Significant impairment of recall at surface of material learned under narcosis	

Time delay before recall is important. In other words, information encoded at depth degrades quickly, and longer delays result in greater loss of information (Morrison & Zander, 2008). Further, more complex or abstract information is lost more quickly than simple information (at depth and on surface), and this too increases with time delay (Morrison & Zander, 2008). As information that has meaning is easier to remember than abstract information (Baddeley, 1966), the quick decay of abstract information (learned and retrieved at depth) may possibly be due to a more 'shallow' encoding of such abstract information (Morrison & Zander, 2008).

Conceptual functions

Studies on the effect of narcosis on conceptual reasoning provide inconsistent results, mainly because of the use of different tests to measure it. In general, reasoning is more impaired with greater depth (Bennett, 1993), and with more unfamiliar material. Table 2.6 presents a sample of the studies done on reasoning to date. Other discussions (Bennett, 1993; Baddeley, 2004) also report that reasoning is impaired, but do not report the extent of such impairment at increased depth. Decrement on reasoning tests has been correlated to cortisol levels at 7 ATA. Higher cortisol levels were associated with better performance (Vaernes & Darragh, 1982), which seems to support the position of the slowed information processing hypothesis that stimulation of the CNS ameliorates the effects of narcosis.

Errors in the recording of arithmetic data have also been reported (Bennett, 2004), but this seems to be a problem of perception rather than mathematical reasoning.

Table 2.6: Studies investigating reasoning.

Pressure	Type of reasoning	Outcome	Source
Unknown	Arithmetic (mathematical reasoning)	Decreased under pressure	Shilling & Willgrube, 1937
61msw (±7 ATA)	Arithmetic task	Decreased from 20 to 15 points on task	Adolfson, cited in Bennett, 1993
76msw (±8.5 ATA)		Errors increased from 6 to 22 (increase of 250%)	
122msw (±13 ATA)		61% less questions correctly answered, with 25% more errors	
6 ATA	Arithmetic task	22% decrement in scores (combination of answers attempted, answered correctly, and errors made)	Fothergill et al., 1991
100fsw (±4 ATA)	Conceptual reasoning test	33% decrement in time to solve problem	Kiessling & Maag, 1962
4 ATA	Visual reasoning (like matrices)	20% impairment in correct answers within time limit	Synodinos, 1976
		But prior practice in shallow water cancels effect totally	
30msw (4 ATA)	Conceptual reasoning (progressive matrices)	26% decrement in performance during day dive	Mears & Cleary, 1980
		36% decrement in performance during night dive	
60msw (7 ATA)	Reasoning test	No significant reduction	Vaernes, 1982
60msw (7 ATA)	Reasoning test	Significant decrease (when processing unfamiliar material)	Vaernes & Darragh, 1982
7 ATA	Number ordination task	14% decrement in performance	Abraini & Joulia, 1992
		16% decrement in performance	Abraini, 1997
7 ATA	WISC Mazes	9% decrement in performance (compared to 1 ATA)	Van Wijk, 2008a
		But possible neuromuscular interference	
	Picture completion task (WAIS)	8% decrement in performance (compare to 1 ATA)	

Psychomotor functioning

Studies on the effect of NN on manual dexterity and motor coordination remain inconclusive. In 1962, Kiessling & Maag found significant impairment at 4 ATA for complex tasks, but since then no evidence has been found that mild states of NN lead to significant psychomotor impairment on simple tasks at pressures within sport diving limits (Abraini, 1997; Abraini & Joulia, 1992; Biersner, Hall, Linaweaver & Neuman, 1978; Gallway et al., 1990). In fact, dexterity appears the neuropsychological function least affect by mild hyperbaric pressure (Abraini & Joulia, 1992; Abraini, 1997; Biersner et al., 1978; Fowler et al., 1985). However, decreased manual dexterity at depth has been reported (see Table 2.7), which potentially could reduce a diver's ability to operate equipment and increase the risk for mistakes during emergencies (Kneller et al., 2012).

Handwriting

Handwriting becomes larger, as narcosis becomes more severe (Bennett, 2004). In a digit-copy task, at 4 ATA breathing air, handwriting became 21% larger in size. This was not affected by practice (handwriting is over-practiced behaviour) (Synodinos, 1976).

Fine visual-motor coordination and finger dexterity

Fine motor manipulation is impaired under pressure, usually from over-exaggeration of movements (Bennett, 2004). If movements are carried out more slowly than usual, the impairment of efficiency is likely to be less severe (Bennett, 2004). Simple motor dexterity is less affected, and complex motor dexterity more affected (often through requiring more time to complete the task, in line with the cumulative slowing of the slowed information processing model). When the Pin Test was administered in water at 4 ATA, a 17% decrement in perceptual-motor skill was found (De Moja et al., 1987). Table 2.7 presents a sample of the fine visual-motor coordination studies done to date.

Gross psychomotor skills

Gross manual skills are more resilient than fine manual skills, but also decrease as depth increases (Bennett, 1993).

Balance

Balance is affected under pressure (in a chamber), and postural difficulties increase as depth increases (Bennett, 1993).

Table 2.7: Studies investigating fine visual-motor coordination.

Pressure	**Task**	**Outcome**	**Source**
76msw (±8.5 ATA)	Manual dexterity	Unaffected	Adolfson, cited in Bennett, 1993
91msw (±10 ATA)	Practical ability	Marked impairment observed	
122msw (±13 ATA)	Manual dexterity	Reduced by 35%	
100fsw (±4 ATA)	Modified Purdue Pegboard	8% decrement in number of parts assembled in 30 seconds	Kiessling & Maag, 1962
5 ATA	Mirror drawing	Only slight depressant effect on psychomotor performance	Frankenhaeuser et al., 1963
170fsw (±7 ATA)	Ring and Peg Test	Simple motor dexterity not significantly affected	Biersner et al., 1978
		Complex motor dexterity significantly affected	
30msw (4 ATA)	Screw-plate test	45% decrement	Mears & Cleary, 1980
36msw (±4.5 ATA)	Ball-bearing test	No effect	Philp et al., 1989
30msw (4 ATA)	Grooved Pegboard	No effect	Gallway et al., (1990)
6 ATA	Purdue Pegboard	9% decrease in parts assembled in 1 min	Fothergill et al., 1991
6 ATA	Manual dexterity test	No effect	Abraini & Joulia, 1992
7 ATA	Manual dexterity test	Small but significant decrements (4%)	Abraini & Joulia, 1992
5 ATA	Digit-letter substitution test	Significant decrement (exacerbated in cases of high anxiety)	Hobbs & Kneller, 2011
4.5–5 ATA	Novel manual dexterity task	12.5% decrease compared to performance in shallow water (<2 ATA) (due to longer time required)	Kneller et al., 2012

Physical sensation and appearance

Impairments of tactile sensation are highly subjective, and include numbness (decreased sensation) of the skin and a tingling sensation in the lips, legs, and feet at great depths (Bennett, 2004). There is no evidence to suggest that tactile recognition is affected. At extreme depths, there is a characteristic deadpan look to the face (Bennett, 2004).

Mood states and social behaviour

The more 'dynamic' aspects of psychological experience of narcosis are a neglected field of research, and only a few studies have examined it in any systematic manner. Most reports of changes in mood, social behaviour, or personality are anecdotal, and it is unclear how such changes were measured.

Reports further use different understandings of the terms 'mood' or 'personality', making interpretation difficult. A few studies reported on these changes accompanying very deep saturation diving, usually while breathing helium-oxygen mixtures, and will thus not be included in this review.

Mood states

At depths below 10 ATA, manic and depressive states may occur, and changes in personality have been reported (Bennett, 2004). At shallower depths (between 4 and 10 ATA), divers may experience feelings of well-being and stimulation similar to the overconfidence of mild alcohol intoxication. Occasionally, terror develops, but this is most likely in a novice diver who is apprehensive in a new environment (Lowry, 2002). Laughter, loquacity, light-headed sensations, feelings of stimulation and excitement might be present. Increased effort at self-control may overcome such behaviour to some extent (Bennett, 2004).

A study by Fowler & Ackles (1972) used rating scales to identify four clusters of adjectives to describe the subjective experience of narcosis, namely:

- euphoria (more carefree, cheerful)
- state of consciousness (more fuzzy, hazy)
- work capability (less effective)
- disinhibitory state (less cautious and self-controlled)

Other studies used self-developed adjective lists to elicit subjective experiences of narcosis (Hamilton et al., 1992, 1995), or more formal adjective-based scales, e.g. modified Subjective High Assessment Scale (SHAS) (Hobbs, 2008; Monteiro et al., 1996).

State of consciousness

There are reports from divers of feeling 'fuzzy', and experiencing their environment as 'hazy' (Hamilton et al., 1995). They describe a slight sense of disconnectedness. At greater depths (90 m+), unconsciousness can occur (Bennett, 2004).

Social and behavioural disinhibition

Divers may become giggly, loud, and boisterous at depth, and display verbosity and uncontrollable laughing, and so forth (Lowry, 2002). Others may become aggressive, irritated, and so forth, apparently mirroring experiences of alcohol intoxication (cited in Hobbs, 2008). As noted previously, at 122 m, orders were appreciated but ignored (Adolfson, cited in Bennett, 1993). Divers may become less cautious and self-controlled (exhibiting symptoms of 'recklessness').

Emotional processing

It has been hypothesised that the Slowed Processing Model may affect emotional processing similarly to information processing (Löfdahl, Andersson & Bennett, 2013). Löfdahl et al. (2013) found that narcosis at 5 ATA was not enough to impair emotional perception or divers' ability to determine pleasantness or unpleasantness of different stimuli. However, their results suggested the possibility of lower arousal for unpleasant stimuli. If this can be confirmed, it may indicate a risk of inappropriate or inadequate reactions to danger in threatening situations (Löfdahl et al., 2013).

2.2.7 High Pressure Nervous Syndrome

HPNS is a condition distinct from the IGN that typically occurs at depths beyond 30 ATA, usually breathing oxygen-helium or other gas mixtures. Signs and symptoms include postural and intention tremors, myoclonia, psycho-sensorimotor disturbances, electro-encephalographic changes, and sleep disorders (Bennett, 2004). Mild effects can be found at pressures from 11 ATA, become marked at 19 ATA, and may be debilitating at over 30 ATA (Lowry, 2002). It has been postulated that this syndrome is not due to gas exposure *per se*, but rather due to a direct effect of pressure on the pre- and post-synaptic membranes (Lowry, 2002).

In contrast to narcosis, there is a greater decrement in psychomotor tests than in intellectual tasks in HPNS. This is due to the associated tremor of hands and arms. HPNS appears to reflect a general excitation of the brain, compared to the decreased excitation seen in IGN (Bennett, 2004).

Overall, divers' mental abilities are sometimes reduced during high-pressure exposures and are sometimes unaffected (cf. Abraini, Martinez, Lemaire, Bisson, Juan De Mendoza & Therme, 1997; Carter, 1979). However, comparisons between studies are difficult, due to the wide variation between experimental conditions (specifically with regard to depth and gas mixtures employed). For example, perceptual speed was alternatively found to be unaffected (Brady, cited in Carter, 1979), or affected to various degrees (Baddeley, cited in Carter, 1979; Carter, 1979; O'Reilly, 1977), at various depths (ranging from 300m to 600+m) , with possibly greater impairment at greater depths (Logue, Schmitt, Rogers & Strong, 1986).

2.3. Human performance in water

Apart from the effects of pressure and narcosis on human behaviour, the underwater environment also exerts its influence. Performance in water is different from performance on land, as a result of the interaction between human and environmental factors. A brief review is included here for the sake of comprehensiveness.

A number of human factors influence complex underwater task performance (Weltman et al., 1970), e.g. experience, ocean vs. dive tank, and situational anxiety. For example, inexperienced divers require increased task completion time, whether they dive in a wet tank or in the open sea. Working in the open sea, rather than in protected wet environments (i.e. a dive tank) further decreases accuracy in task completion. Higher levels of situational anxiety also contribute to poorer performance.

2.3.1. Environmental factors

Task loading

Task loading refers to the increase in decision-making and tasks during underwater activity. Irrespective of the purpose of an underwater excursion, diving is a multi-task environment. Firstly, there is the focus on the primary purpose of the dive – the 'job at hand', as well as routine monitoring of vital information (usually displayed on gauges) – time, gas supply, depth, etc., and secondly, continuous vigilance is required to changes in the environmental conditions (sea conditions, etc.). Adding tasks stresses a diver's ability to function effectively (Egstrom & Bachrach, 2004).

Water medium

The water effect has previously been mentioned. Some examples include movements in a viscous medium that are patently different from those performed in air (Egstrom & Bachrach, 2004); the relative weightlessness in a tractionless setting too is a problem that affects the use of tools because of recoil, and it makes it difficult to maintain a stable posture (Egstrom & Bachrach, 2004). Several writers emphasise the influence of being in water, unrelated to hyperbaric pressure, as a dominant cause of reduced cognitive functioning (Nevo & Breitstein, 1999). Baddeley & Idzikowski (1985) reviewed research in this area and concluded that, at depths of up to 30 metres, the water effects can account for up to half of the cognitive impairments reported. Recent studies indicated that, even at shallow depths (i.e. 1.5 ATA), cognitive functioning – as measured by multiple choice reaction, tracking, and sustained attention – is impaired (Dalecki, Bock & Schulze, 2012), supporting the idea that water effects may account for a significant component of cognitive impairments reported in studies on NN.

Visibility

Low visibility – through obscuring elements in the water – decreases performance by making observing and completing tasks more difficult (Egstrom & Bachrach, 2004). "Divers often have to resort exclusively to tactile sensory inputs when faced with loss of visibility" (Egstrom & Bachrach, 2004, p.332). This becomes increasingly problematic if the turbid water is cold and the diver needs to wear protective gloves, which markedly diminishes sensation (Egstrom & Bachrach, 2004). Vision *per se* is also altered underwater, but as it falls outside the scope of this thesis, will not be discussed here.

Temperature

The most disruptive environmental condition is temperature, and the most severe stress in diving is cold exposure. While divers' tactile sensitivity is not significantly affected by prolonged underwater submersion *per se* (McKee, 1972), cold temperature does adversely affect performance, and protective measures (e.g. gloves) reduce mobility and manual performance (Egstrom & Bachrach, 2004), especially finger dexterity in cold conditions (Imamura, Rissanen, Kinnunen & Rintamäki, 1998). The relationship between cold water exposure and performance on tasks involving tactile sensitivity, grip strength, and finger dexterity has been well established (Egstrom & Bachrach, 2004), with divers' tactile sensitivity decreasing linearly with decreased finger skin temperature at 5 ATA (Zander & Morrison, 2008).

Immersion in cold water at shallow depths impairs memory significantly, with up to a 70% loss of memory for data learned at depressed core temperatures (Baddeley, Cuccaro, Egstrom, Weltman & Willis, 1975; Coleshaw, Van Someren, and Wolff, 1983). Further, a distraction effect of cold water with regard to performance on higher-order tasks (peripheral vigilance, navigational problem solving, and arithmetic) is found after short periods in shallow water (Parsons, 2003; Vaughan, 1977). Decreased ability to recall information due to cold exposure is attributed either to the fact that it was not initially attended to, or to a failure that occurred during some stage of information processing (Morrison & Zander, 2008). In summary, cold exposure appears to affect divers' cognitive and information-processing abilities, which are required for task completion underwater (Coleshaw et al., 1983; Egstrom & Bachrach, 2004).

Protective clothing

The effects of cold on performance are exacerbated by the use of protective clothing (e.g. gloves), which may limit tactile sensation, fine form perception, and fine manual manipulation.

2.3.2. Tactile perception

No previous studies with hyperbaric pressure and tactile performance *per se* could be located. Recent studies supported the idea that narcosis slows but does not distort information processing, but they do not support the idea that narcosis *per se* has pervasive effects on perceptual sensitivity (Fowler, Pang

& Mitchell, 1992). It can be assumed that the effects of cold temperature and the wearing of gloves will have additive effect on decrements of manual performance.

2.3.3. The elements of performance sequencing

The classical elements of performance sequencing (Egstrom & Bachrach, 2004) are:

1) perception – sensing the stimulus event (which may be visual, tactile, or auditory),
2) information processing – the cognitive or mediational processing through which the information perceived is evaluated and a course of action (a motor response) is selected, and
3) motor response – the performing of a motor activity that completes the task.

From the above review, it is thus clear that all three elements are vulnerable to the effects of narcosis.

All three elements are affected in some way during episodes of narcosis in open water. An example of a diver inserting a bolt may clarify the relevance for this study:

1) In a low-visibility scenario, divers need to rely on tactile perception to gain information about a task, and to complete that task successfully (through a continuous task progress feedback loop). If cold water or protective clothing interferes with tactile stimuli, it will affect task performance. For example, the diver needs to monitor whether the bolt is placed into the right opening in the right way.
2) Narcosis interferes with information processing, in disrupting the speed of processing, rather than disrupting the structures involved. The time to evaluate tactile information and deciding on a particular motor response will be extended. Since the information processing is complex – a diver has to comprehend the stimulus, do the mental spatial rotation, and translate that to fine motor manipulation, before a course of action can be initiated – processing speed is hypothesised to be reduced significantly (resulting in longer completion times). For example, this may then require extended time for a diver who needs to place the bolts accurately and to tighten them correctly.
3) Motor responses may be affected by environmental conditions (e.g. cold) and by the effects of narcosis on psychomotor functioning, as well as possible influences of anxiety and the water medium.

2.4. Psychological constructs

The measurement of a number of psychological constructs was included in the study, and this is thus reviewed here for the sake of comprehension.

2.4.1. Anxiety

Although many highly anxious persons tend to self-select out of diving, anxiety is common among divers (Colvard & Colvard, 2003; Morgan, 1995), and in reality, moderate anxiety may be beneficial in keeping the diver focussed. However, it has been demonstrated that, as divers' stress and subsequent arousal increases, so their general (non-narcotic) performance decreases (Griffiths, 2002). Elevated anxiety may have a significant effect on manual dexterity, quite separate from any narcotic effect (Hobbs & Kneller, 2011; Kneller et al., 2012).

As noted previously, anxiety exacerbates the effects of narcosis, and especially the impairment of psychomotor functioning (Baddeley & Idzikowski, 1985; Davis et al., 1972; Kneller et al., 2012; Mears & Cleary, 1980). It has been suggested that anxiety interferes in task performance because it causes – or exacerbates – muscular tension, thus impairing motor rather than cognitive skills (Baddeley, 2004). In support of this idea, in a small local study, self-reported anxiety was not correlated to performance on visual scanning and reasoning at 7 ATA (Van Wijk, 2008a) – both cognitive tasks. Two recent studies (Hobbs & Kneller, 2011; Kneller et al., 2012) found that divers with high self-report anxiety performed significantly poorer on a psychomotor task at 5 ATA than did divers with low self-report anxiety (although both groups still experienced significant performance decrement due to narcosis as well). Anxiety thus combines with any narcotic effect to magnify the functional impairment.

The dangers of a hostile environment may further potentiate the effects of narcosis (Baddeley et al., 1968; Baddeley, 1972), possibly through the mechanism of increased anxiety. Thus, danger may elicit anxiety (through the mechanism of cognitive appraisals), which leads to increased arousal, which in turn leads to perceptual narrowing. Perceptual narrowing is a narrowing of attention – where individuals concentrate more on central features of the task, and less on more peripheral ones (Baddeley, 1972). This resultant perceptual narrowing may then be a function of anxiety, rather than narcosis *per se*.

The effect of anxiety can also be conceptualised through increased arousal that leads to increased metabolic activation, with the resultant cardiovascular and respiratory consequences, including fatigue, hypoxia and CO_2 retention, which were earlier mentioned to potentiate the effects of narcosis.

The nature of the relationship between anxiety and narcosis has not yet been clarified. Fowler et al. (1985) suggested that it may have an additive effect, i.e. the combined effects of narcosis and anxiety might be equal to their separate impacts. Other studies, reviewed in Hobbs & Kneller (2011) showed that the apparent impairment caused by narcosis alone, and anxiety alone, did not add up to the extent of impairments observed. This suggested that anxiety and narcosis were combining in a synergistic manner, rather than an additive one, to produce a combined effect that is larger than the sum of their isolated effects; Hobbs & Kneller (2011) recently reported preliminary evidence of such a synergistic relationship. However, no comprehensive theory explaining the nature of the anxiety-narcosis relationship currently exists, as other factors also need to be considered (e.g. the effects of cognitive appraisal, distractibility, and increased metabolic activation and its physiological and biochemical implications).

When considering non-pathological anxiety, it is necessary to distinguish between trait and state anxiety. Trait anxiety represents an enduring feature of a person's personality, and reflects a person's general experience of anxiety. The State-Trait Anxiety Inventory (STAI) and the State-Trait Personality Inventory, Trait Anxiety (STPI) (Spielberger, 1995) are the most used measures of trait anxiety. Trait anxiety is also referred to as dispositional anxiety.

State anxiety is a person's current emotional state. It is transient and context dependant, responding to cognitive appraisals of danger or threat, as well as available resources. State anxiety is also referred to as situational anxiety.

Trait anxiety was originally identified as a predictor of panic in beginning diving students (Griffiths, Steel, Vaccaro, Allen & Karpman, 1985), and recent studies confirmed that trait anxiety accurately predicts panic behaviour during diving training in novice scuba divers (Morgan, Raglin & O'Connor, 2004), but not in experienced scuba divers (Colvard, 2007). One mechanism could be the association between high trait anxiety and measures of chronic elevated arousal (Takahashi, Ikeda, Ishikawa, Kitamura, Tsukasaki, Nakama & Kameda, 2005). As previously discussed, an increase in arousal can improve performance under narcosis, up to a point, but thereafter it becomes counter-productive (Dodge-Yerkson law). It is noted that divers with high self-report anxiety also more subjectively report 'intoxication' at 5 ATA (Hobbs & Kneller, 2011).

2.4.2. Mood states

The term 'mood' can refer to the global set of affective states we experience on a day to day basis (Fox, Boutcher, Falkner & Biddle, 2000), in other words, a relatively stable affective state, or it can refer to transient mood states (like situational anxiety), or it can refer to clinical conditions that describe affective disorders.

At depths below 10 ATA, manic and depressive states may occur, and although it is often unclear how these are defined, it seems to follow the interpretation of earlier versions of the *Diagnostic and*

Statistical Manual: Handbook of Psychiatric Conditions. Transient mood changes are more likely to occur at shallower depths (4 to 9 ATA) than clinical changes in affect. Subjective states of narcosis will be described in the next section. Pre-dive mood state may also affect performance during EHE.

For the purposes of this study, mood will be defined as "a set of feelings, ephemeral in nature, varying in intensity and duration and usually involving more than one emotion" (Lane & Terry, 2000, p. 17). In this definition, pre-dive mood states may affect performance through the mechanism of increased arousal (e.g. in elevated tension, anger, or vigour) or decreased arousal (e.g. depression), or through distraction (e.g. the presence of strong mood-content), or through a mood state of fatigue and exhaustion.

2.4.3. Subjective experience of narcosis

As noted, subjective symptoms of narcosis may influence performance through shifts in the value of strategic variables. This is exacerbated by the phenomenon of subjective adaptation, where divers believe they have adapted to or compensated for narcosis, although this belief is unsupported by objective evidence.

An older study by Fowler & Ackles (1972) identified four clusters of adjectives to describe the subjective experience of narcosis. Recent studies borrowed from research on alcohol intoxication, and used standardised scales of adjective lists (e.g. the Subjective High Assessment Scale [SHAS]) (Hobbs, 2008; Monteiro et al., 1996) to quantify the extent of subjective change.

The concepts of subjective experiences of narcosis and mood states may at times overlap, confounding their use in research on altered states of being.

2.5. Tactile perception

While the focus of this study is on the neuropsychological (behavioural) effects of NN, a brief mention of tactile perception is appropriate here.

Tactile object recognition requires the integrity of transducers, primary sensory processes, and higher-order perceptual processes in the association cortex (Caselli, 2003). Interference at any of these levels will impair object recognition in different ways. For most types of object recognition, spatial acuity, or form perception, is of special importance. The slowly adapting type 1 (SA1) receptor-afferent unit is the critical peripheral limb of the spatial system concerned with somesthetic processing of form, with the somatosensory association cortices located in the parietal lobe (Caselli, 2003). Only a very slight stimulus is required for shape recognition (Mountcastle, LaMotte & Carli, 1972; Vega-Bermudez, Johnson & Hsiao, 1991). Familiar shapes, handled by blindfolded subjects, are normally recognised very quickly (90% of cases within 5 seconds), accurately (87–99%), and symmetrically between the two hands (Caselli, 2003).

2.6. Summary of salient findings

A review of the available literature on neuropsychological effects of narcosis clarifies a number of issues relevant to this study:

1) Greater pressure is required to elicit clear signs and symptoms of NN, especially at more than 4 ATA, which would mean that a depth of at least 5 ATA is required for this study. The current study eventually used an equivalent depth of 6 ATA; the reasoning behind this is explained in Chapter 4 (Section 4.4.2)
2) Tasks that are more complex show the signs and symptoms of NN more clearly, and as diving is a complex task environment, any measuring tool needs to be more complex too. Chapter 4 describes the use of a measuring task that is more complex, requiring the integration of tactile form perception, mental manipulation, and motor coordination.
3) Psychomotor performance (manual dexterity) is not expected to be significantly affected at 6 ATA, and thus any decrement in performance on a tactile task will probably be the result of impairment of cognitive processing (e.g. tactile perception, mental manipulation) or psychological variables.
4) Tactile tasks require good psychomotor coordination, which leaves it open to the influences of anxiety (whether congenital or situational), requiring the inclusion of a measurement of anxiety.
5) It is not clear whether age, education, or extent of previous technical exposure will have any effect on tactile performance.

2.7. Problem setting

This chapter reviewed the current knowledge regarding neuropsychological manifestations of NN. It exposed a number of shortcomings in the current body of knowledge. In particular, the human performance effects of hyperbaric pressure on tactile perception and tactile memory have not been systematically studied. It is further not clear, how exactly psychological factors (e.g. anxiety, mood states) and biographical factors (e.g. age, education, technical experience) would influence tactile perception and memory performance under conditions of hyperbaric pressure. The correlation between subjective experiences of narcosis, tactile performance, and psychological and biographical variables is also unknown.

From this brief summary, a number of study directions can be formulated, and Chapter 3 will present the objectives of the current study in more detail.

CHAPTER 3: PURPOSE OF THE STUDY

The literature review in Chapter 2 set the scene for framing the research problem. It was found that very little work has been done on the tactile modality, and relatively little on subjective experiences of narcosis, and the influence of personal mood states on performance under narcosis. Chapter 3 will describe the rationale of the study, and formulate the specific detailed objectives of the research design.

3.1. Rationale of study

The commercial diving environment is typically a low visibility environment. In a task environment where visibility has deteriorated, individuals rely on tactile perception as a primary mode of data acquisition. To complete tasks that are more complex, they need to translate tactile information into three-dimensional mental images and to solve problems mentally, before translating it back to motor actions, with tactile sensation acting as the feedback mechanism.

When these actions happen under hyperbaric conditions, other factors, like IGN, may influence a person's ability to complete such tasks successfully. As noted, a search of the available literature did not find any studies investigating the effect of experimental hyperbaric exposure (EHE) on tactile performance or tactile memory. This then leads to three broad questions: 1) Does EHE affect tactile performance, and if so, would training moderate this effect? 2) Does EHE affect tactile memory, and if so, would training moderate this effect? and 3) Would certain psychological and biographical variables influence these relationships?

These questions were investigated using the Tupperware Neuropsychological Task (TNT), certain psychological measures and biographical data.

The TNT measures neuropsychological constructs relating to tactile form perception, mental transformations, fine motor coordination, tactile memory and visuo-spatial organisation, which are all important for diving. The psychological measures give an indication of trait anxiety, general mental health, mood states, and subjective experiences of narcosis. These constructs are all important for successful (i.e. safe) diving, and would thus influence decisions regarding fitness to dive, and more importantly, decisions regarding fitness to return to diving after accidents and mishaps. The effects of prior training on hyperbaric performance ('learning') are important to provide recommendations to the commercial diving industry. In order to achieve this, there is a requirement to understand the effect of EHE on these issues.

3.2. Specific objectives

3.2.1. Primary objectives

1) To describe the effect of EHE (at 6 ATA) on the neuropsychological constructs of tactile performance

This will enable academic description of the EHE effects of NN on the above constructs, and might assist in supporting or furthering theories explaining the mechanisms of narcosis.

2) To describe the effect of EHE (at 6 ATA) on delayed tactile memory

This will enable academic description of the EHE effects of NN on tactile memory, and might assist in supporting or furthering theories explaining the mechanisms of narcosis.

3.2.2. Secondary objectives

3) To investigate the influence of psychological factors on neuropsychological performance (i.e. tactile performance and memory) under conditions of EHE (at 6 ATA):
   a. using measures of trait anxiety
   b. using measures of transient mood states
   b. using subjective rating of narcosis

4) To investigate the effect of biographical factors on neuropsychological performance under conditions of EHE (at 6 ATA):
   a. age and gender
   b. formal education (academic and technical)
   c. previous technical exposure (formal and informal)
   d. diving qualification
   e. self-rating of technical competence

5) To explore whether performance at 1 ATA can be used to predict performance at 6 ATA.

6) To investigate the use of visual recordings of behaviour at depth for the qualitative analysis of neuropsychological performance under conditions of EHE.

3.3. Retrospective objectives

In the course of the practical research, a number of other issues were raised, and resulted in a few objectives being added retrospectively:

7) To investigate possible effects of the rate of compression on the TNT performance at 6 ATA.

8) To explore the psychometric properties (including factor analysis and internal consistency and reliability analysis) of the SHAS.

3.4. Conclusion

Chapter 3 stated the individual primary and secondary objectives of the study. Although there are a number of objectives, they can all be reached through a relatively simple research design. Chapter 4 will describe the research protocol for collecting the data to achieve these objectives.

CHAPTER 4: METHODOLOGY

4.1. Introduction

In order to achieve the objectives set out in the previous chapter, a relatively simple research protocol was developed. This chapter will introduce the methods employed in the study, and describe the participants, the measuring instruments, the experimental conditions, the procedures, the data management and analysis, and the ethical considerations.

The study employed a simple cross-over design. Participants were randomly allocated to the two study groups. One group completed a neuropsychological task at 1 ATA, and then at 6 ATA, while the other group completed the same task in the reverse order. Figure 4.1 gives a schematic representation of the basic cross-over design protocol. All the abbreviations in the figure are described in Sections 4.2 and 4.3.

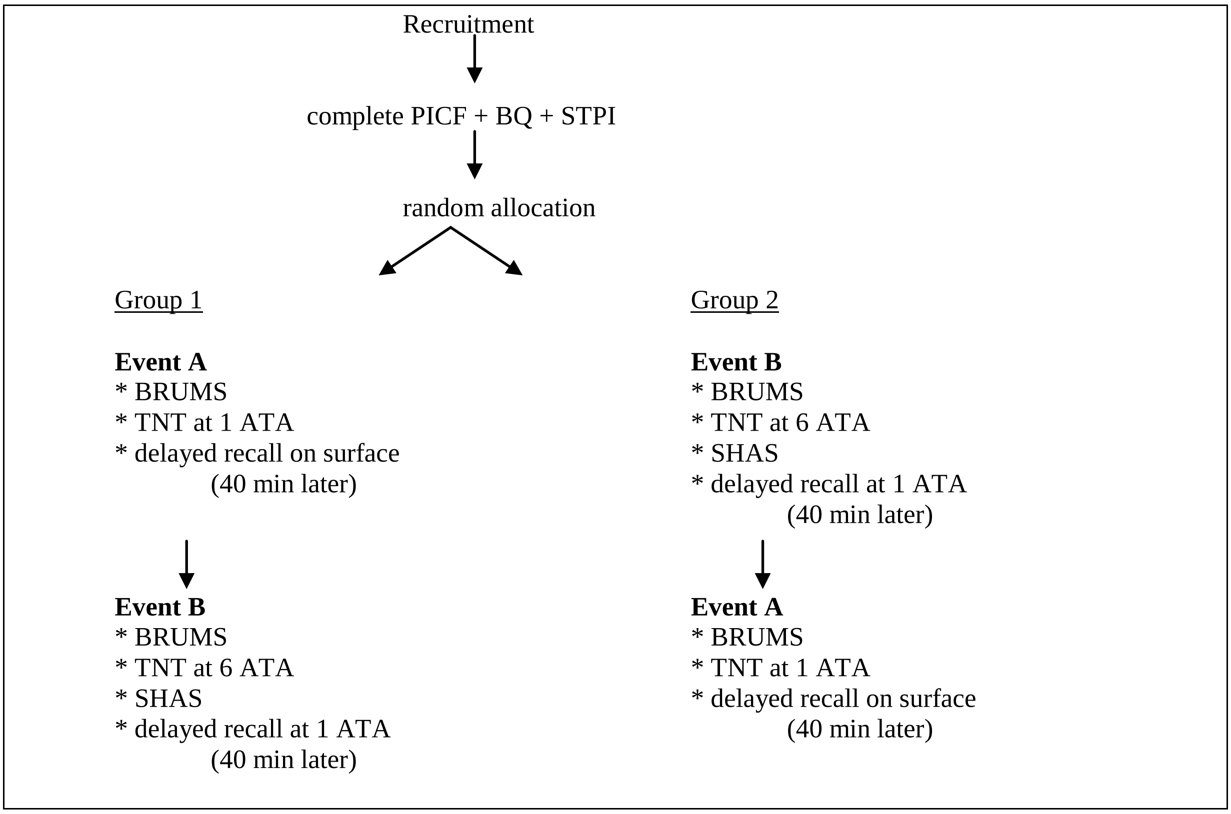

Figure 4.1: Cross-over design groups.

4.2. Participants

In order to complete the dive at 6 ATA, participants needed to be qualified to dive to 50msw. Participants were therefore recruited from commercial diving schools. They were ideally suited for this: they were under training for hyperbaric work, thus reducing any danger of participating in deeper dives, while at the same time they had little previous exposure to NN, and thus less opportunity to learn compensatory strategies for working at depth. Using commercial diving students had two further advantages. Firstly, all the students were medically fit for diving, reducing the need for special medical screening prior to inclusion. The depth of the hyperbaric exposure also corresponded to their training requirements for chamber dives, reducing the need for additional dives. Secondly, all the dives were closely supervised by experienced instructors, adding an additional safety buffer to the process.

Participation was voluntary only, and all students from the participating commercial diving schools were invited to participate. Volunteers received a thorough briefing before signing a consent form, prior to entering the study. The Participant Information and Consent Form (PICF) was approved by the Health Research Ethics Committee of Stellenbosch University (reference number N11/06/176), and can be found in Addendum A. A total number of 120 participants were required. The volunteers were randomly assigned to either Group 1 or Group 2. Participants did their chamber dives in groups, and groups were alternatively designated as either Group 1 or Group 2.

Candidates with particular risk for adverse psychological response, as identified by the psychological measures (and confirmed by a clinical psychologist), were to be excluded from further participation, and referred to an appropriate mental health service provider. None were identified. Instructions for the testing and the psychological scales are standardised in English, and candidates who did not have a basic proficiency in English would have been excluded. As the training of commercial divers is done in English, it was not expected that this pool would contain any candidates who lacked basic English knowledge.

Inclusion criteria:

Potential participants had to meet all of the following criteria before being accepted for enrolment into the study:

- Must be an enrolled student at one of the participating commercial diving schools
- Must be on a diving training course, which trains the students to dive to 50m in a chamber
- Must be at least 18 years of age
- Must have a valid diving medical certificate (in terms of the Diving Regulations, 2009)

- Must have signed the informed consent form
- Must be able to read and speak basic English (instructions for the TNT and the psychological scales are standardised in English).

Exclusion criteria:

Potential participants who met any one of the following criteria were not eligible for inclusion in the study:

- Adverse neuropsychological history (history of motor vehicle or other accidents with traumatic brain injury or loss of consciousness, and cerebro-vascular accidents)
- Psychological conditions, which render the person unsuitable to complete the study tasks at those depths
- Physical conditions that would render dexterity sub-optimal (e.g. missing digits on fingers).

4.3. Measures

4.3.1. Measuring tactile performance

Diving is a complex task environment, and thus any tool measuring performance needs to be complex too. At the same time, any such tools need to be administered simply and quickly under conditions of increased EHE; in addition, they should be widely accessible, and they must have good metric characteristics. Tactile performance was measured using the Tupperware Neuropsychological Task (TNT), which also formed the basis of the memory tasks. This is a complex task, requiring the integration of tactile form perception, mental manipulation, and motor coordination.

Tupperware Neuropsychological Task (TNT)

The Tupperware Neuropsychological Task is based on the Tupperware™ *Shape O Toy*, which consists of a round ball that has 10 different shapes cut out of it, and 10 three-dimensional shapes that correspond to the cut-outs. The different shapes are triangle, pentagon, square, cross, circle, star, trapezium, pie wedge, hexagon, and oval. The purpose is to find the right shapes for the corresponding cut-outs, and then to fit them into the cut-out.

To isolate any visual effects on tactile performance, the *Shape O Toy* is completed blindfolded, without prior opportunity to see the ball or shapes. This way, mental manipulation is also based on tactile (not visual) perception, and motor coordination is based on tactile (not visual) feedback mechanisms.

There is a standardised instruction set, and participants are asked to complete the task against time. Participants may use both hands, in any way they prefer. Their score is the total number of shapes completed in 10 minutes (TNT-tt). South African (SA) standardisation data is available (Van Wijk, 2011a).

The TNT's association with the underlying constructs of tactile form perception, three-dimensional spatial perception, and fine motor manipulation has been established previously (Van Wijk, 2010, 2011a), and no significant correlations were found with age, education, anxiety or any gender effects (Van Wijk, 2011a). The TNT incorporates the classical elements of performance sequencing mentioned in Section 2.3.3, namely: 1) perception – sensing the stimulus event (in this case tactile), 2) information processing – the cognitive or mediational processing through which the information perceived is evaluated and a course of action (a motor response) is selected, and 3) motor response – the performing of a motor activity that completes the task.

Between 35 and 40 minutes after completion of the task, participants were requested to draw as many of the shapes they could remember on an A4 sheet of paper, to measure tactile memory. This provides for a 'delayed recall score', which was the total number of correctly recalled shapes (TNT-dr). Visuo-spatial perception can be observed in the organisation of the drawings. In this study, the time delay of between 35 and 40 minutes was chosen, as this was the time required for safely completing the dive with adequate decompression. They were not warned of this task prior to the first administration.

A previous study with the TNT (immediate tactile memory) recall in SA revealed no significant correlation with age, education, or anxiety, but reported that men displayed significantly better immediate recall that women (Van Wijk, 2011a). The TNT recall correlates well with similar measures of tactile memory, as well as with measures of three-dimensional spatial perception and mental manipulation (Van Wijk, 2010).

The memory modality here is referred to as 'tactile' memory, to distinguish it from a purely verbal or purely visual memory modality. However, the wording is problematic, as it is not purely tactile either. In this case, individuals perceived the stimulus through their tactile senses, but also needed to translate it to a picture (i.e. to visualise it) in their mind in order to manipulate it (mentally and physically). Their delayed memory recall was then presented visually (by drawing the shapes). The difficulty in accurately naming the memory modality is acknowledged as problematic, and will be dealt with again in the discussion.

Two minor adaptations were made to the TNT for use in this study: Firstly, the A4 sheet of paper was replaced with a slate for drawing the shapes in the chamber. Secondly, the blindfold was replaced with a removable blackened diving mask, to obstruct visual access to the task.

There is a danger that other factors may confound performance on tactile perception tasks. It can also be argued that, as only a slight stimulus is required for shape recognition, environmental factors (e.g. temperature, gloves) should not significantly interfere with transduction (Mountcastle et al., 1972; Vega-Bermudez et al., 1991). Further, in normal persons, recognition is fast and accurate, and both hands are equally good at it (Caselli, 2003). Fine motor dexterity is less affected by narcosis, and should not be significantly impaired at 6 ATA. Thus, any impairments of performance on the TNT could probably be attributed to cognitive (i.e. cortical) processing. In spite of this argument, some variables (e.g. anxiety, temperature, etc.) were included in the data, to ensure that they were controlled in the analyses.

4.3.2. Measuring psychological variables

State-Trait Personality Inventory, Trait Anxiety (STPI)

Anxiety is known to decrease performance under hyperbaric pressure (Hobbs & Kneller, 2011; Mears & Cleary, 1980; Moeller et al., 1981). Acute anxiety was measured with the Brunel Mood Scale (BRUMS), but trait anxiety was measured by the STPI, Form Y (Spielberger, 1995). Trait anxiety represents an enduring feature of a person’s personality, and reflects a person’s general experience of anxiety.

The STPI is a self-administered questionnaire designed to measure dispositional anxiety in adults. Only the 10-item trait anxiety subscale was used in this study. The ‘trait’ items, which are rated on a four-point frequency scale, aim to assess the subject's emotional disposition. Scores range from 10 to 40, with higher scores indicating a greater level of emotion.

The STPI Form Y, which was originally published in North America, was validated using male and female navy recruits, college students, and working adults. Its main strengths are its ease of administration and scoring, and its high validity and reliability. Alpha coefficients in the norm groups ranged from .81 to .96, with the coefficients being highest in the working adults test group. Full references to reliability and validity, and other psychometric information can be found in Spielberger (1995). The USA population mean is 15 for men and 17 for women. The only SA norms available are for the SA Navy, with a mean of 14 (±4) for both women and men (Van Wijk, 2008b).

This instrument was ideally suited for the study, for two reasons: Firstly, some normative data for the SA sample was available (based on SA Navy employees). Secondly, the STPI has been used extensively in other studies involving divers. For example, Morgan et al. (2004) managed to predict 83% of panic events among scuba students, using trait anxiety. Colvard (2007) found that using the STPI population average only predicts 21% of panic events in experienced scuba divers, but when using the STPI average score +1 standard deviation, the overall prediction rate goes up to 81%. Higher STPI scores further somewhat predict selection outcomes for SA Navy diving courses, as well as greater injury-proneness during military diving training (Van Wijk, 2011b). The STPI has also been recommended for studies investigating the relationships between anxiety and narcosis (Hobbs & Kneller, 2011). An example of the STPI can be found in Addendum C.

Brunel Mood Scale (BRUMS)

The STPI described above was used to measure stable, enduring anxiety. In contrast, transient mood states were recorded with the BRUMS. This 24-item scale measures six identifiable affective states through a self-report inventory, with respondents rating a list of adjectives on a 5-point Likert scale (Terry & Lane, 2003). It is based on the Profile of Mood Scales (POMS) (McNair, Lorr & Droppleman, 1992), a widely used measure to assess transient affective mood states (McNair, Heuchert & Shilony, 2003). It has proved an excellent measure of current mood states and their fluctuations in many diverse groups (McNair et al., 2003; Nyenhuis, Yamamoto, Luchetta, Terrien & Parmentier, 1999; Terry, Lane, Lane & Keohane, 1999). Good concurrent and criterion validity has been reported internationally (Terry et al., 1999; Terry, Lane & Fogarty, 2003), and research on SA samples showed acceptable internal consistency (Terry, Potgieter & Fogarty, 2003; Van Wijk, 2011c).

The factors of the BRUMS are described in the following way (Terry et al., 1999): Anger is typified by feelings that vary in intensity from mild annoyance or aggravation to fury and rage, and is associated with arousal of the autonomic nervous system (Spielberger, 1995). Confusion is proposed to be a feeling state characterised by bewilderment and uncertainty, associated with a general failure to control attention and emotions. Depression is associated with a negative self-schema characterised by themes such as hopelessness, personal deficiency, worthlessness, and self-blame (Beck & Clark, 1988). Fatigue is typified by feelings of mental and physical tiredness. Tension is typified by feelings such as nervousness, apprehension, worry, and anxiety. Vigour is typified by feelings of excitement, alertness, and physical energy.

It should be noted that the six affective mood states' subscales are not diagnostic indicators, but refer to sub-clinical psychological states ('mood states'). Using a formula, a total mood distress (TMD) score can be calculated from the six subscales.

Recent research used the BRUMS to investigate mood in sport and exercise (Lane, Jackson & Terry, 2005; Lane, Milton & Terry, 2005; Lowther & Lane, 2002), and predicting dichotomous (win/lose) outcome in some sport competitions (Terry & Munro, 2008). It has further been used in studies examining the effects of weight loss (Caulfield & Karageorghis, 2008), and risk for eating disorders (Terry & Galambos, 2004) and athletic sport injuries (Devonport, Lane & Hanin, 2005; Galambos, Terry, Moyle, Locke & Lane, 2005), the effect of hormones on mood (Coutts, Rogerson, Deakin, Marshall-Gradinsnik, Meir, Zhou & Wetherby, 2006), and mood changes during pregnancy (Petersson, 2008), emotional intelligence (Lane, Thelwell & Devonport, 2009), sleep profiles (Pedlar, Lane, Lloyd, Dawson, Emegbo, Whyte & Stanley, 2006), and academic performance (Lane, Whyte, Terry & Nevill, 2005; Thelwell, Lane & Weston, 2007).

The BRUMS can be used with different instruction sets, depending on the requirement (Terry & Lane, 2003). The “How you feel right now” instruction set was utilised in this study. South African norms are available (Van Wijk, 2011c), and could be used to determine problematic psychological distress.

A previous South African study found that, although some of the BRUMS subscales might have limited value in predicted selection outcomes for SA Navy diving courses, the scale did have value in predicting injury-proneness during military diving training (Van Wijk, 2011b). The precursor of the BRUMS (the POMS) has also been recommended for studies investigating the relationships between anxiety and narcosis (Hobbs & Kneller, 2011). See Addendum D for an example of the BRUMS. In the present study, the Tension subscale was also used to measure state anxiety.

Modified Subjective High Assessment Scale (SHAS)

The SHAS was originally developed for the assessment of subjective effects of alcohol (Judd, Hubbard & Janowsky, 1977). The current version most often used (standardised by Schuckit & Gold, 1988) asks respondents to indicate their current feelings on 12 items, each of which is rated from a score of 0 (none) to 36 (extreme). The test-retest reliability of the SHAS is approximately 0.80, with a Cronbach alpha of 0.96 overall (Schuckit, Smith, Kalmijn, Tsuang, Hesslebrock & Bucholz, 2000).

The SHAS was first used in relation to induced narcosis by Monteiro et al. (1996), who used the scale for their participants to self-rate their feelings on the 12 items (from 0 to 36), when intoxicated with alcohol, and at hyperbaric pressure equal to 6 ATA (while sober). They found a high inter-individual variability among their subjects, and strong correlations between their subjective feelings when they were intoxicated and when they were experiencing narcosis.

More recently, Hobbs (2008) used a modified version of the SHAS to extend the Monteiro et al. (1996) study to 40 metres below the surface of the sea, and replicated their findings. His modified version of the SHAS used a 0 to 100 rating scale, and replaced one adjective ('sweating') with 'intoxicated'. The Hobbs (2008) modified version was used in this study, using a rating scale from 1 to 10. An example of the modified SHAS can be found in Addendum E.

4.3.3. Measuring biographical variables

Age and education may affect the time to complete tactile performance tests (Prigatano & Parson, 1976), and thus need to be included when analysing the results. Technical skills, through over-learning, may be particularly resistant to the effects of depth induced narcosis, and a rating on the diver's technical proficiency and prior exposure needs to be included in the analysis as well.

Biographical Questionnaire (BQ)

Biographical information was elicited through the completion of a BQ, which provided space for the participant to note their name, age, gender, formal education (academic, technical, and diving qualifications), and technical proficiency (experience in formal technical work environment, informal exposure, and self-graded technical competency).

There was also a section inquiring into any relevant medical history – mental health, head injuries, serious illness, or other organic issues. The STPI was incorporated into the BQ for ease of administration. Addendum B contains an example of the BQ.

4.3.4. Other data

Where possible, task completion at 6 ATA was video recorded. While this allowed for additional control of the experimental context, it was also used to explore the value of qualitative analysis of visual recordings of behaviour under conditions of EHE.

4.4. Experimental conditions

4.4.1. Normobaric assessment

Normobaric testing took place on the surface, wearing loose coveralls. Participants completed the BRUMS prior to commencing with the TNT testing (timed test and delayed recall), and the SHAS was completed afterwards. The delayed recall was tested after 35 – 40 minutes.

4.4.2. Hyperbaric assessment

Hyperbaric testing took place in a dry pressure chamber, at a pressure of 6 ATA (607.95 kPa), while participants were breathing air and dressed in loose coveralls.

The EHE equivalent to a depth of 50msw, or 6 ATA, was chosen for the following reasons: The effects of NN are generally expected to appear from 30msw. However, wide individual variation occurs, and some individuals only present with the signs and symptoms under increased pressure. It was hypothesised that, to ensure that performance outcomes could be attributed to NN, 1 ATA more than the minimum threshold was required to ensure sufficient EHE. The effect of narcosis on performance is also greater under wet (sea) than dry (chamber) conditions (Baddeley & Idzikowski, 1985; also see Kneller et al., 2012 for discussion). To compensate for this, the study used a further 1 ATA above the threshold. Thus a working pressure of 6 ATA was determined. This pressure is also the practical limit, as commercial divers working deeper would use mixed gases to reduce the effects of NN.

The cross-over design used here served to control for other variables, so that mechanism of difference during the EHE could be attributed to the effect of NN.

4.4.3. Testing sites

Three commercial diving schools participated. They were the Professional Diving Centre in Durban, the Sea Dog Commercial Diving School in Saldanha, and the Research Diving Unit, Department of Oceanography, University of Cape Town. Standard chamber dive profiles, and equipment, were used. As noted, testing took place during scheduled chamber training dives to 6 ATA.

4.4.4. Technical details of dives

The different diving schools use different chambers. All dives had between three and six participants in the chamber, wearing loose unrestrictive clothing. The rate of compression of chambers depended on the pressure of available high pressure air, the size of the chamber, the number of occupants (to fill space), and so forth, thus each individual ‘dive’ in the same chamber might have been different. This was further a multi-site study, and all these factors could differ across sites too. As the rate of compression might have an effect on NN (Bennett, 2004), this became a confounding factor in the study. However, it also allowed the opportunity to add another objective retrospectively – namely to investigate possible effects of rate of compression on neuropsychological performance at depth.

The breathing mixture was maintained at 21% oxygen, and during each dive, the chamber was flushed regularly to enhance the quality of the air and to moderate the effects of increased temperature and CO_2 build-up.

4.5. Procedure

As noted, volunteers were recruited though the commercial diving schools. The volunteers received a briefing, and completed the participant information and consent forms. When they were accepted into the study, they also completed the BQ (including STPI).

As mentioned, the study employed a cross-over design (schematically represented in Figure 4.1.), in order to control for practice effects. Each participant completed the BRUMS immediately prior to each dive and the modified SHAS immediately afterwards.

Group 1 (naïve to the task content) completed the TNT and after 35–40 minutes, the delayed recall task. Both were done in the chamber, at 1 ATA. Group 1 then did the same tasks at 6 ATA, on the same day.

Group 2 (also naïve to the task content) completed the TNT in the chamber at 6 ATA, and after 35–40 minutes, the delayed recall task at 1 ATA. Group 2 then did the same tasks at 1 ATA, on the same day.

The TNT was completed 'blind' (i.e. without visual aid), by using a removable blackened mask. Participants from the different 'dives' had no contact with each other, and were thus not exposed to any of the experimental procedures by other participants.

To limit going into extended decompression time, administration of the TNT at 6 ATA was designed to span exactly 10 minutes, and the score was calculated in terms of how much of the task they had completed in that time. The TNT was administered according to strict standardisation guidelines, and supervised by a clinical psychologist positioned outside the chamber. Completion of all paperwork was also supervised by a clinical psychologist, who also conducted the memory recall measurement.

4.6. Data management

4.6.1. Data recording

Biographical details and STPI profiles completed by the participants on entry into the study were codified by the researcher, and entered into a data spreadsheet

The BRUMS profile and SHAS for each task administration was also codified by the researcher and entered into the data spreadsheet. Each participant completed the BRUMS and SHAS themselves. Actual scores for task completion – number of shapes completed (TNT-tt) and number of shapes recalled (TNT-dr) – were captured by the researcher directly onto the electronic data spreadsheet.

4.6.2. Description of data

All the study findings will be described using appropriate statistical measures, including tables, graphs and descriptive statistics. Results from the TNT-tt and TNT-dr were recorded as proportional data (score out of 10), and will be described in terms of means and standard deviations. Results from the psychological scales and some biographical markers were recorded as ratio data, while the rest of the biographical results were recorded as nominal data. Where appropriate, effect sizes will also be reported.

4.6.3. Statistical analysis

The statistical analysis is presented per objective. The primary focus of the statistical analysis was to describe the effects of EHE and other personal variables, and with the secondary focus being to find correlations to develop predictions, although other techniques were also included.

Objective 1 aims to describe the effect of EHE (at 6 ATA) on the neuropsychological constructs of tactile performance. This was calculated with a repeated measures ANOVA.

Objective 2 aims to describe the effect of EHE (at 6 ATA) on delayed tactile memory. This was calculated with a repeated measures ANOVA.

Objective 3 aims to investigate the correlations between psychological factors and neuropsychological performance (i.e. tactile performance and memory) during EHE (at 6 ATA), using measures of trait anxiety and transient mood states, and subjective ratings of narcosis. Spearman’s correlation was calculated for neuropsychological performance and trait anxiety, transient mood states (using all six subscales and the total score), and subjective rating of narcosis.

Objective 4 aims to investigate the correlations between biographical factors and neuropsychological performance (i.e. tactile performance and memory) during EHE (at 6 ATA). Spearman's correlation was calculated for neuropsychological performance and age, formal education, previous technical exposure, and previous diving experience.

Objective 5 aims to determine whether surface performance can be used to predict performance at depth. To examine this, correlation coefficients were calculated using the data from Group 1.

Objective 7 aims to investigate the possible effect of the rate of compression on neuropsychological performance (i.e. tactile performance and memory) during EHE (at 6 ATA). The rate of compression was categorised into three levels, and its effect was calculated using a one-way ANOVA. The rate of compression was operationalised through consensus by the participating diving schools into three categories: fast (< 3 min), moderate (3 – 4 min), and slow (> 4 min).

Multiple regression analysis, using psychological, biographical, and dive data, was also employed to explore potential interactions with TNT results.

The SHAS has never been used in South Africa before, and to meet Objective 8, the scale was subjected to psychometric analysis (including factor analysis and internal consistency and reliability analysis).

All statistical tests were performed by using:

- SPSS (IBM SPSS Statistics, version 20, IMB Corp, 2011), and
- STATISTICA 7 (Statsoft, 2008).

Sample size calculation

On the TNT-tt, participants generally completed on average 7.5 shapes in 10 minutes, with an SD of 3. For the EHE condition, 2 less (i.e. 5.5) was considered significant. To detect this difference with a power of 0.9 and a confidence interval of 95%, a sample size of 96 (48 per group) was required.

It was expected that 20% of participants would render unusable records, and another 20% was thus added to the sample, leading to an eventual round total number of 120 candidates required for this study. The secondary objectives would require impractically larger sample sizes, and would thus be analysed, but with lower power results.

Qualitative analysis

Objective 6 aims to explore the use of visual recordings of behaviour at depth for the qualitative analysis of neuropsychological performance during EHE. This was done using thematic analysis, following the guidelines set out in Silverman (2012, p.336–337).

4.7. Ethics

4.7.1 Autonomy and informed consent

The study was approved by the University of Stellenbosch's Health Research Ethics Committee (reference number N11/06/176). Participants were volunteers recruited from commercial diving schools. Potential participants received a thorough briefing, with opportunity for asking questions. The consent forms were then signed individually, which gave a further opportunity to discuss questions and concerns. This was all done prior to the study. An example of the Participant Information and Consent Form (PICF) can be found in Addendum A.

4.7.2 Confidentiality

Completed psychological scales were placed in sealed envelopes, which were opened by the researcher. For standardisation, the researcher personally conducted all the task administrations and recorded the results on the electronic data spreadsheet, and only the researcher had access to participants' named data.

4.7.3 Non-maleficence and safety

Participants were only included if they were medically fit for hyperbaric exposure. All participants were diving students, implying that they were medically fit for diving and already undergoing training for deep dives, and that all dives were supervised carefully, thus minimising any potential risk.

The only deviation from their normal chamber dive procedure was the use of the blackened diving mask while completing the TNT. It was removed (by the diver) directly on completion of the TNT (and after the completed TNT was secured in a bag). The participant divers were all familiar with diving in low-visibility conditions.

No discomfort was reported, as expected, as participants generally viewed this as an adventure (thus the reason for their volunteering for the study). The only risks were those associated with hyperbaric exposure, and this was strictly controlled through the standard safety procedures enforced by the commercial diving schools. Participants were informed that they could withdraw from the study at any time (this was included in the PICF).

4.7.4 Beneficence

Participants in this study did not have any direct benefits from the study. However, contact with the psychologist provided an opportunity for recognizing conditions adverse to completion of diving training or general mental health. It was foreseen that in such cases appropriate referral or follow-up would be done; however, this was not necessary. Referral would be for clinical management, and not fitness-to-dive assessment.

The study recorded 'baseline' information for the participants. In line with the practical intent of the study, should any participant be injured in future (e.g. neurological decompression sickness), these scores could be used in subsequent evaluations.

4.7.5 Justice

This study did not exploit any vulnerable population, or discriminate against any population. Any person meeting the inclusion and exclusion criteria was eligible for inclusion.

4.8. Conclusion

This chapter set out the methodology utilised, including the participants, the measurements taken, and the experimental conditions of this cross-over study. The next chapter will present the results of the data analysis.

CHAPTER 5: RESULTS

5.1. Introduction

Chapter 4 discussed the methods used in the study. This chapter will first describe the demographic profiles of the respondents who participated in the study, and then extend it by presenting the findings of the psychological measures. The results of the statistical analyses will then be presented per objective. The chapter will conclude with a thematic analysis of the video recordings. For ease of reading, some of the objectives and methods will be briefly presented here again.

5.2. Participants

Although the initial protocol required 120 participants, 139 participants eventually completed the full procedure and were included in the study sample. The larger number was attributed to the high level of interest generated among the divers at the various schools, and as the data was available, it was decided to include all of it to increase the statistical power of the results. A total number of 70 divers completed the testing in the order of 1 ATA followed by 6 ATA (Group 1), while 69 completed it in the reverse order (Group 2).

The three diving schools represented mainly younger divers (mean age = 26.8 ± 5.9, range 18 to 44) and participants were mainly male (87%). In general, they came from southern and western Africa and the Indian subcontinent, with smaller numbers coming from Europe. Their academic achievements are summarised in Table 5.1, as are the diving courses in which they were enrolled. The majority of the group had no formal technical qualification (83.5%). The rest had different levels of formal training, but as the different levels had few participants in each, they were collapsed into a single group with technical training (16.5%) for statistical analysis.

Table 5.1: Distribution of academic achievement and current diving courses.

Academic achievement	Did not complete high school	8.6%
	High school certificate	56.1%
	Formal post school vocational training	20.9%
	University degree	10.1%
	Post graduate degree	4.3%
Current diving course	Class IV	49.6%
	Class III	31.7%
	Class II	18.7%

Most of the participants had no previous formal technical work experience (73.4%), while 18% had between 1 and 2 years of experience, and 8.6% had worked for three years or more in a technical job. Further, 57.5% of participants indicated that they had no informal exposure to technical work or other activities, while 32.4% indicated that they had some informal exposure, and a further 10.1% had a large amount of informal exposure. Participants were also asked to self-rate their technical competence on a scale from 1 (not good) to 10 (very good). Scores ranged from 1 to 10, with the mean at 6.5 (±1.6). The median score was 7. There were no significant differences between the two subgroups on any of the above variables.

5.3. Psychological measures

The STPI is a self-administered questionnaire designed to measure dispositional anxiety in adults. Scores range from 10 to 40, with higher scores indicating a greater level of trait anxiety. The mean score on the STPI was 16.2 (±3.9), which follows both the (American) manual and SA mean scores closely. There were no gender differences, and no correlation with age. There were no significant differences between the two subgroups on the STPI.

The BRUMS measures six transient mood states, which is usually presented in a graphic profile. The profile of the total group is presented in Figure 5.1, and the mean scores and variance in Table 5.2.

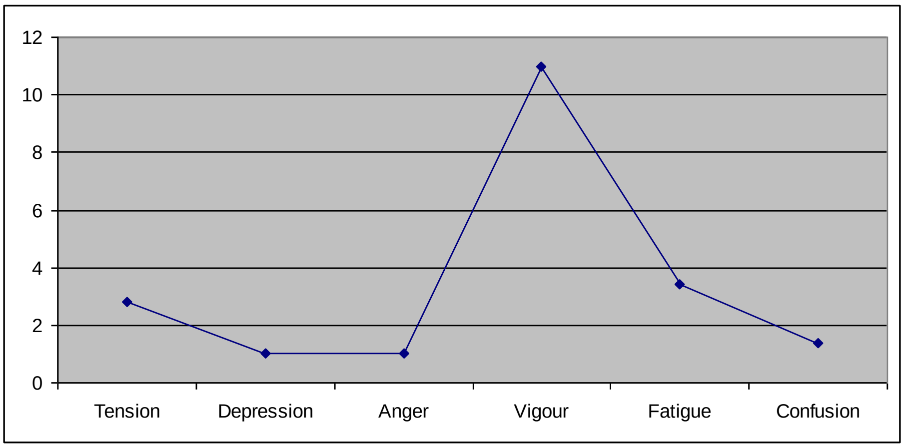

Figure 5.1: BRUMS profile of total group according to mood states.

The BRUMS profile in Figure 5.1 and Table 5.2 represents the typical desired profile (Devonport et al., 2005), with only a slight elevation on the tension and fatigue states, which could possibly be attributed to the observation that all the candidates were busy with their respective commercial diving courses, and about to enter what was for most of them the first dive to 6 ATA. There were no significant gender differences or correlation with age, and no significant differences between the two subgroups on the BRUMS.

Table 5.2: Mean scores and variance of BRUMS mood states.

	Mean	**Variance**
Tension	2.8	5.1
Depression	1.0	3.0
Anger	1.0	2.0
Vigour	11.0	14.9
Fatigue	3.4	11.3
Confusion	1.4	3.3

The SHAS was used for divers to self-rate their feelings under conditions of EHE at 6 ATA, on the 12 items, on a scale from 0 to 10. Only 40 participants rendered useful SHAS scores. As can be expected, there was wide inter-individual variation, with the mean composite score = 26.8 with a standard deviation of 16.4 (previous studies did not use composite scores). There were no significant differences between the two subgroups on the SHAS. Psychometric exploration of the SHAS is reported in Section 5.8.4.

5.4. Objective 1

Objective 1 aimed to describe the effect of EHE (at 6 ATA) on the neuropsychological constructs of tactile performance. Participants' performance scores were subjected to a repeated measures ANOVA. There was no violation of the assumption of sphericity, and the results can be found in Table 5.3.

EHE had a statistically significant effect on the participants' tactile performance ($F_{1,137}$ = 63.694, p < 0.01), with a large effect size value (η_p^2=.32). There was no significant effect from the order of task completion. Thus, divers' performance deteriorated significantly on the TNT-tt at 6 ATA, compared to 1 ATA, and this finding held, irrespective of the sequence in which they completed the TNT. Figure 5.2 provides a graphic representation of the results.

Table 5.3: Results from repeated measures ANOVA.

		Wilk's Lambda	**F**	**Df**	**p**	**η_p^2**
TNT-tt	Condition	.683	63.694	1,137	.000	.317
	Condition*Sequence	.993	0.983	1,137	.323	.007
TNT-dr	Condition	.727	51.554	1,137	.000	.273
	Condition* Sequence	.965	4.940	1,137	.028	.035

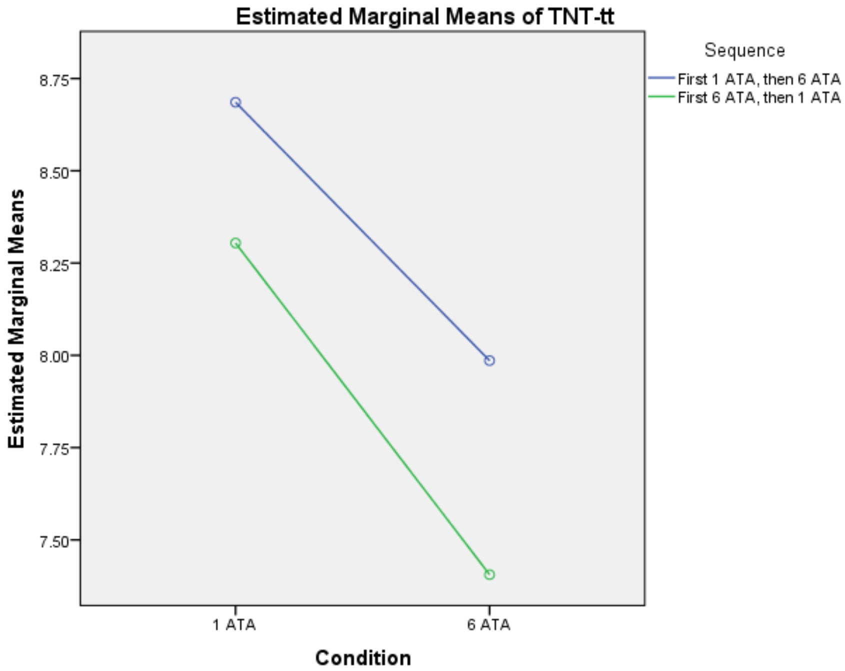

Figure 5.2: Means of TNT-tt performance under different conditions and in different sequence.

5.5. Objective 2

Objective 2 aimed to describe the effect of EHE (at 6 ATA) on delayed tactile memory. Participants' performance scores were subjected to a repeated measures ANOVA. There was no violation of the assumption of sphericity, and the results can be found in Table 5.3.

EHE had a statistically significant effect on the participants' tactile memory ($F_{1,137}$ = 51.554, p < 0.01), with a large effect size value ($\eta_p{}^2$=.27). There was further a significant effect of the sequence of task completion ($F_{1,137}$ = 4.94, p < 0.05), with a small effect size value ($\eta_p{}^2$=.04). Thus, divers' delayed recall performance deteriorated significantly after the 6 ATA dive, compared to after the 1 ATA administration of the TNT. Further, participants who did the 6 ATA test first did significantly more poorly (i.e. remembered less) than those who did the 1 ATA test first. Figure 5.3 provides a graphic representation of the results.

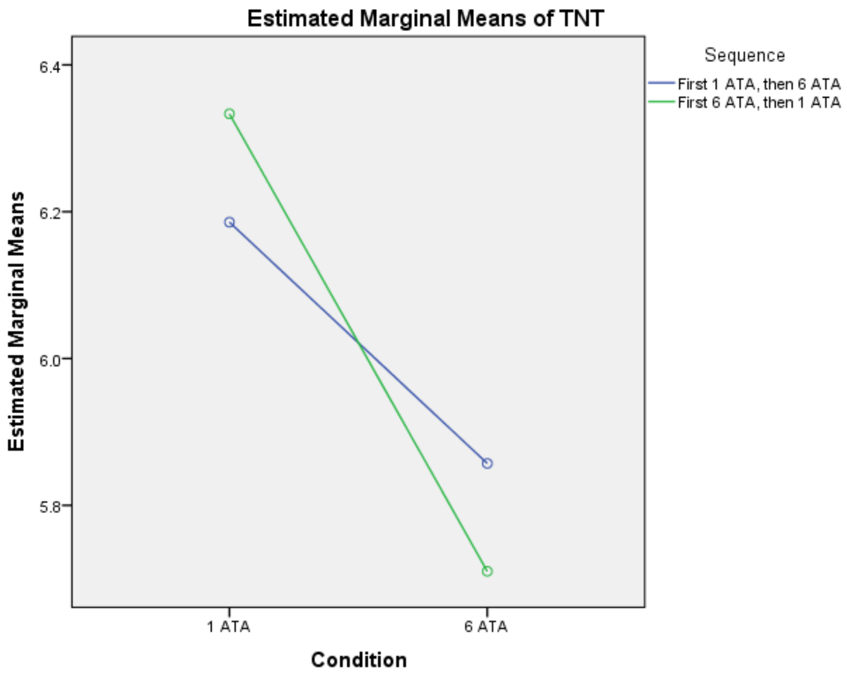

Figure 5.3: Means of TNT-dr performance under different conditions and in different sequence.

5.6. Objective 3

Objective 3 aimed to investigate the influence of psychological factors on neuropsychological performance (i.e. tactile performance and memory) during EHE (at 6 ATA), using measures of trait anxiety, transient mood states, and subjective ratings of narcosis. Spearman's correlation was calculated for neuropsychological performance and psychological measures (trait anxiety, and transient mood states – using all six subscales and the TMD score) and subjective rating of narcosis (SHAS). Four markers of neuropsychological performance were used, namely performance during EHE (both TNT-tt and TNT-dr at 6 ATA), as well as the calculated size of the difference between performance at 6 ATA and 1 ATA (for both TNT-tt and TNT-dr).

There was a significant but small negative correlation between trait anxiety and performance on the TNT-dr after the 6 ATA dive. Divers with higher trait anxiety recalled less of the TNT shapes afterwards. There was also a significant but small negative correlation between transient tension (as a measure of state anxiety) and the difference in TNT-dr scores between 1 and 6 ATA. Participants who reported more tension showed a larger decrement in performance when completing the TNT-dr across conditions (i.e. poorer performance at 6 ATA than at 1 ATA). There was a further significant but small negative correlation between reported fatigue and performance on the TNT-tt at 6 ATA. Divers who reported more fatigue completed fewer of the TNT shapes. No other correlations between the STPI or BRUMS and performance at 6 ATA or the size of the difference between 1 and 6 ATA were found. The results are shown in Table 5.4.

Table 5.4: Correlations between psychological variables and neuropsychological performance.

	Performance at 6 ATA		**Difference between 6 ATA and 1 ATA performance**	
	TNT-tt	**TNT-dr**	**TNT-tt**	**TNT-dr**
STPI	-0.06	-0.23**	-0.07	0.10
Tension	-0.11	-0.03	-0.08	0.17*
Depression	-0.15	-0.02	-0.12	-0.02
Anger	-0.05	-0.07	-0.03	0.02
Vigour	-0.03	-0.09	0.01	-0.10
Fatigue	-0.20*	-0.11	-0.13	0.00
Confusion	-0.08	-0.03	-0.07	0.00
TMD	-0.13	-0.04	-0.10	0.08

* $p < 0.05$

** $p < 0.01$

Performance on the TNT-dr after the 6 ATA dive was significantly correlated to the subjective narcosis experiences of being anxious, uncomfortable, and tense (moderate correlations). The difference in TNT-dr scores between 1 and 6 ATA was significantly correlated to the subjective narcosis experiences of being confused and light-headed, and difficulty concentrating (moderate correlations). The results can be found in Table 5.5.

Table 5.5: Correlations between SHAS scores and neuropsychological performance (N=40).

	Performance at 6 ATA		**Difference between 6 ATA and 1 ATA performance**	
	TNT-tt	TNT-dr	TNT-tt	TNT-dr
High	0.14	0.18	-0.01	0.41
Anxious	0.28	0.57**	0.08	0.11
Confused	-0.31	0.10	-0.15	0.51*
Elated	0.37	-0.23	-0.08	-0.16
Dizzy	0.09	0.13	0.30	0.15
Nauseous	-0.03	0.10	-0.11	0.06
Uncomfortable	0.19	0.46*	0.03	0.35
Light-headed	0.13	0.15	0.22	0.49*
Weak	0.18	-0.02	0.03	0.16
Tense	0.24	0.47*	0.04	0.18
Intoxicated	0.29	0.07	0.19	0.11
Difficulty concentrating	0.05	0.24	-0.23	0.50*

* $p < 0.05$

** $p < 0.01$

5.7. Objective 4

Objective 4 aimed to investigate the influence of biographical factors on neuropsychological performance (i.e. tactile performance and memory) during EHE (at 6 ATA). Spearman's correlation was calculated for neuropsychological performance, and for age and self-rated technical competence. T-tests for independent samples were calculated for gender and technical qualification, while one-way ANOVA's were used to investigate the effects of academic attainment, diving qualification, formal technical work experience, and informal exposure to technical activities.

The same four markers of neuropsychological performance as in the previous section were used, namely performance during EHE (both TNT-tt and TNT-dr at 6 ATA), as well as the calculated size of difference between performance at 6 ATA and 1 ATA (for TNT-tt and TNT-dr).

Age showed significant correlations with TNT-dr at 6 ATA, as well as with the difference in TNT-tt scores between 1 and 6 ATA. Older participants recalled fewer shapes after the 6 ATA dive, and further showed a larger decrement in performance in completing the TNT-tt across conditions (i.e. they showed poorer performance at 6 ATA than at 1 ATA). The results can be found in Table 5.6. Self-rated technical competence showed no significant correlation to any of the neuropsychological markers.

Table 5.6: Correlations between biographical variables and neuropsychological performance.

	Performance at 6 ATA		**Difference between 6 ATA and 1 ATA performance**	
	TNT-tt	**TNT-dr**	**TNT-tt**	**TNT-dr**
Age	0.03	-0.26*	0.25*	-0.11
Self-graded technical competence	-0.13	0.15	-0.13	0.04

* p < 0.01

T-tests for independent samples showed no significant effect of gender or technical qualification on any of the neuropsychological markers. Academic attainment influenced TNT-dr scores ($F_{4,134}$ = 10.437, p < 0.01), where participants who did not complete high school recalled significantly fewer shapes after the 6 ATA dive than did the rest (p < 0.01 for all). Diving qualification also influenced TNT-dr scores ($F_{2,136}$ = 5.349, p < 0.01), where Class II divers recalled significantly more shapes after the 6 ATA dive than did the Class III divers (p < 0.01). Formal technical work experience and informal exposure to technical activities played no significant role in performance.

5.8. Other objectives

5.8.1. Objective 5

Objective 5 aimed to determine whether surface performance could be used to predict performance at depth. To examine this, correlation coefficients were calculated using the data from subgroup Group 1 (who completed their first task at 1 ATA, before doing the same at 6 ATA).

There was a significant correlation between TNT-tt on the surface and at 6 ATA (r = .71, $p < 0.0001$) (see Figure 5.4), as well as between TNT-dr after the surface testing and after the 6 ATA dive (r = .90; $p < 0.0001$) (see Figure 5.5). Tactile performance on the surface thus appears to be a good indicator of performance under conditions of EHE at 6 ATA.

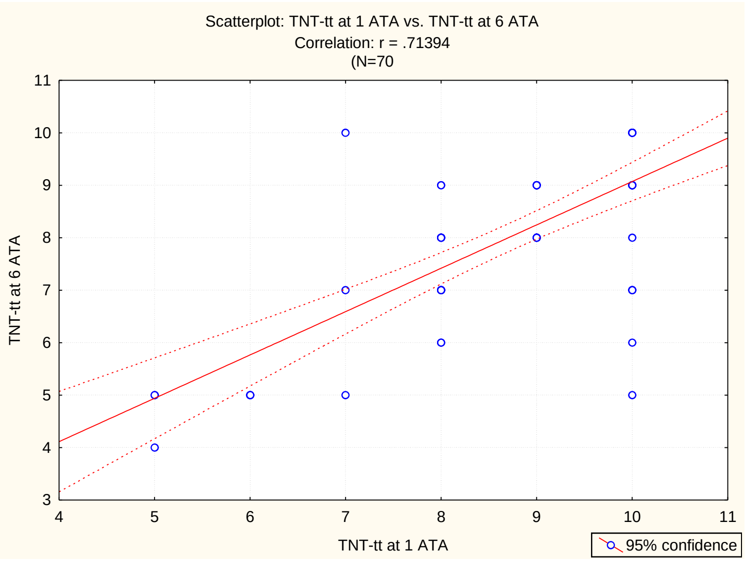

Figure 5.4: Scatterplot of TNT-tt at 1 and 6 ATA.

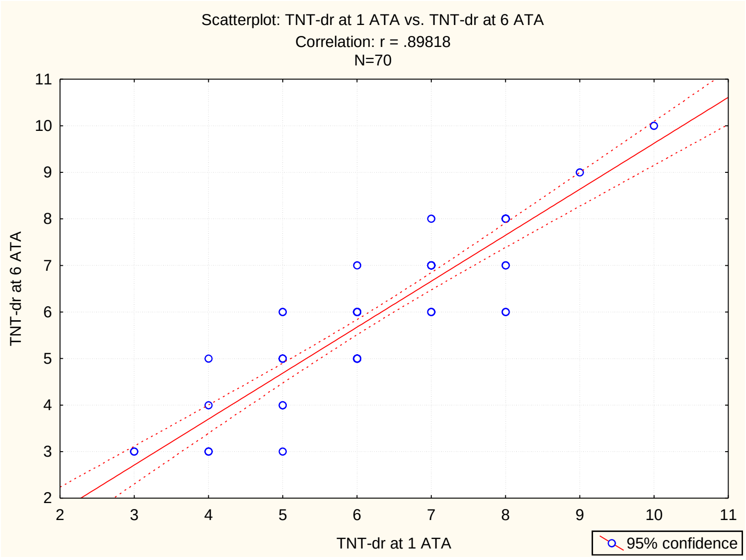

Figure 5.5: Scatterplot of TNT-dr at 1 and 6 ATA.

5.8.2. Objective 7

Objective 7 aimed to investigate the possible effect of the rate of compression on the neuropsychological performance during EHE (at 6 ATA). The rate of compression was categorised into three levels, and its effect was calculated using a one-way ANOVA. The rate of compression was operationalised through consensus by the participating diving schools into three categories: fast (< 3 min), moderate (3 – 4 min), and slow (> 4 min).

No significant differences could be found between the participants who were compressed more quickly and those who were compressed more slowly.

5.8.3. Multiple Regression Analysis

In order to explore the relative contribution of the indicated psychological and demographic variables to performance at 6 ATA, they were subjected to a multiple regression analysis (MRA). As performance on the TNT-tt was not significantly influenced by any of the variables measured, only the TNT-dr was entered as the dependant variable.

The data was analysed by means of multiple regression, using as regressors age, academic attainment, dive qualification, STPI, Tension and Fatigue. The regression was a rather poor fit (R^2_{adj} = 15%), but the overall relationship was significant ($F_{6,132}$ = 4.910, $p < 0.01$). Age (β = -.26, $p < 0.01$), academic attainment (β = .18, $p < 0.05$), dive qualification (β = .20, $p < 0.05$), and trait anxiety (β = -.24, $p < 0.01$) each made significant but small contributions to the prediction of recall after the 6 ATA chamber dive, while the contribution of tension and fatigue was not significant.

5.8.4 Objective 8

The Subjective High Assessment Scale (SHAS) has never been used in South Africa before, and Objective 8 aimed to explore the psychometric properties of the scale, including its internal consistency, reliability analysis and factor analysis. The SHAS is a 12-item self-rating instrument measuring subjective feelings when under conditions of narcosis. Items are again scored from 0 (“not at all”) to 10 (“extremely”). Data from this study indicated that the SHAS showed acceptable internal consistency, with a full scale Cronbach alpha =.774.

A principal component factor analysis with varimax rotation produced a three-factor structure (Table 5.7). The three factors together accounted for 72.70% of the total item variance. A cut-off point of 0.4 for item loadings was then chosen for practical reasons (Dawis, 2000) and items loading <0.4 were excluded from further analysis. Two items (“nauseous” and “weak”) failed to load on any of the factors.

Items loading substantively on Factor 1 referred to the high feelings of intoxication, e.g. high, elated. Factor 2 incorporated experiences of physical anxiety or discomfort, e.g. tense, uncomfortable. Factor 3 referred to experiences of cognitive suppression, e.g. confused, difficulty concentrating.

Table 5.7: Factor loadings for varimax three-factor solution.

Item		**Loading**
Factor 1: Feelings of intoxication		
	(Cronbach alpha = .785)	
	(Eigenvalue = 3.386)	
1.	High	0.676
4.	Elated	0.650
5.	Dizzy	0.734
8.	Light-headed	0.763
11.	Intoxicated	0.753
Factor 2: Feelings of physical anxiety or discomfort		
	(Cronbach alpha = .844)	
	(Eigenvalue = 2.462)	
2.	Anxious	0.890
7.	Uncomfortable	0.781
10.	Tense	0.903
Factor 3: Feelings of cognitive suppression		
	(Cronbach alpha = .734)	
	(Eigenvalue = 1.422)	
3.	Confused	0.867
12.	Difficulty concentrating	0.869

Using the factor scores may help to expand the analysis in Section 5.6. There was a significant positive correlation between Factor 2 (physical anxiety and discomfort) and performance on the TNT-tt at 6 ATA (r = .57, p < = 0.01). There was also a significant positive correlation between Factor 3 (cognitive suppression) and the difference on TNT-dr between 1 and 6 ATA (r = .57, p < = 0.01).

5.9. Objective 6

Objective 6 aimed to explore the use of visual recordings of behaviour at depth for the qualitative analysis of neuropsychological performance during EHE. This was done using thematic analysis, following the guidelines set out in Silverman (2012, p. 336–337).

Before the main themes are reported, a note on the limitations may be useful to frame the interpretation of the results. The main limitation was the small number of dives (N=8) that were recorded *and* that produced observable behaviour. This was mainly due to the expected distorted audio records (due to voice distortion at air pressure of 6 ATA) and the poor lighting in the chambers. The results of this analysis are therefore not necessarily representative of all the chamber dives conducted for this study. Against this background, the findings are presented, firstly, to support other observations from the literature and, secondly, to guide future systematic studies. As a further aid to interpret the understanding of participants' experience at 6 ATA, participants' feedback during the debriefing after the chamber dives is included as part of the qualitative nature of this analysis. Three themes – not totally unrelated to each other – emerged from the analysis.

Theme 1: Focus

It appeared that increased concentration could compensate to some extent for the effect of NN. Individuals with a greater task focus performed better (i.e. completed the TNT-tt more quickly). Further, individuals who engaged in casual communication in the chamber experienced greater distraction, performing more poorly (i.e. completed the TNT-tt more slowly). When matching an individual's observed behaviour with the time he or she had taken to complete the TNT-tt, it was clear that those who talked more took longer (i.e. completed fewer shapes) than those who did not talk. The compensatory effect of task focus supports the observation of Bennett (2004), namely that increased effort may to some extent overcome some of the effects of NN.

Theme 2: Following instructions

Some participants during each dive forgot the instruction to start the task (at 6 ATA), even though they had had at least two briefings prior to the dive, and some even completed the task during the

1 ATA administration. They had to be reminded via the intercom. This phenomenon was visible throughout most of the chamber dives, not only the ones recorded.

In spite of their failure to initiate the task spontaneously (after being signalled to do so at depth), they did respond appropriately when cued via the intercom. Divers thus remembered the instructions (i.e. what to do), but neglected to execute the task spontaneously, requiring the chamber operator to prompt them to do so. This was somewhat surprising, as the purpose of these chamber dives was to complete the TNT. It is hypothesised that the failure to initiate task completion was a result of distraction, as the slowest to start were also those displaying signs of social disinhibition (e.g. excessive laughter, loquacity).

Theme 3: Shape memory

Two issues emerged relating to shape memory, in part informed by the feedback during the debriefing immediately after each chamber dive. Firstly, participants subjectively experienced the tactile form identification and manipulation as easy to accomplish. They found it more difficult to match the shapes to the cut-outs, commenting that NN interfered with their immediate memory of the shape – they reported difficulties remembering the exact nature of the shape (e.g. how many sides or angles it had), when searching for the right cut-out (and *vice versa* had difficulty remembering how many sides the cut-out had when searching for the correct shape to fit). This required them to re-feel the shape or cut-out repeatedly, adding time to their performance. This was visible in the video recordings.

Secondly, a few participants reported that, during the TNT-dr administration, they knew that there were only a limited number of basic shapes, and thus presented their "delayed recall" responses from "general memory", rather than from recently acquired memory. However, due to the study design, this should not affect the memory outcome.

5.10 Conclusion

Chapter 5 reported the results of this study and, amongst other things, found that NN affected tactile performance, irrespective of the sequence of testing. It also affected tactile memory, although the sequence of testing also played a role here.

Higher trait anxiety was associated with poorer recall, higher state anxiety was associated with larger decrement in recall performance, and fatigue was associated with poorer TNT-tt completion. Subjective experiences also played a role, where feelings of physical anxiety (i.e. increased arousal) were associated with better recall, and feelings of cognitive suppression (decreased arousal) were associated with a larger decrement in recall performance. Older age was associated with poorer recall and a larger decrement in TNT-tt performance. Lower academic attainment was associated with poorer recall, while higher diving qualification was associated with better recall. In spite of the significant associations, these factors made only small contributions to performance variance. Performance on the surface was a good predictor of performance at depth. Qualitative analysis rendered three themes, namely focus vs distraction, following instructions, and shape memory. Some psychometric properties of the SHAS were also reported.

The next chapter will discuss the findings, offer some comments on the methodology, and conclude with some recommendations.

CHAPTER 6: DISCUSSION AND CONCLUSION

6.1. General discussion

6.1.1. Tactile performance under conditions of experimental hyperbaric exposure

This study found that EHE has a significant effect on tactile form perception, mental manipulation and fine motor coordination, with a decrement of 9.5% calculated at 6 ATA compared to performance at 1 ATA (in terms of blocks completed within time). The effect was significant, irrespective of the sequence of testing. The magnitude of the effect was the same for all participants, independent of their psychological or biographical profile. This suggests that any effects can be attributed to NN alone.

Motor dexterity is considered less affected by narcosis, and should not be significantly impaired at 6 ATA. Thus, any impairments of performance on the TNT could probably be attributed to the cognitive processing of tactile performance. In this regard the results obtained with the TNT are not inconsistent with predictions from the Slowed Processing Model. The TNT is a complex task, requiring tactile perception, mental translation and manipulation, planning and psychomotor execution, with feedback and then a repeat of the process. This task complexity makes it particularly susceptible to the cumulative effects of slowed information processing. In the light of the performance sequencing discussed in Section 2.3.3, the consequences of slower task completion would hold true for many underwater tasks in the commercial diving industry. Fortunately, tactile performance on the surface appears to be a good indicator of performance during EHE of 6 ATA, suggesting that practice produces a learning effect.

These findings have two ready implications for industry, namely the importance of planning more time for complex tasks (especially in low visibility), and the value of practicing complex tasks on the surface or in shallow water.

Finally, previous studies found little effect of NN on performance on the Grooved Pegboard (GP; Gallway et al., 1990) at 4 ATA. While the GP is less complex than the TNT, there is a strong positive association between performance on the GP and the TNT (Van Wijk, 2010). It could be hypothesised that observable performance decrements on tasks of tactile perception and psychomotor speed may only appear at greater depths than 4 ATA.

6.1.2. Tactile memory under conditions of experimental hyperbaric exposure

This study found that EHE had a significant effect on delayed tactile memory, with a decrement of 8% calculated after a 6 ATA chamber dive compared to performance at 1 ATA (in terms of shapes recalled). Although this effect was visible in both directions of testing, divers who completed the task first at 1 ATA did not do as poorly after the 6 ATA test, suggesting a possible spill-over effect from their first exposure (at 1 ATA). Participants who did the task first at 6 ATA did not do as well after the 1 ATA test, suggesting that there was little effect from their first exposure. It would then appear that previous surface memory of a specific task may improve recall of the same task during and after a 6 ATA chamber dive.

With regard to prior exposure, delayed tactile recall on the surface appears to be a good indicator of tactile recall after a deep dive, suggesting that previous (surface) exposure might produce a beneficial effect.

No previous studies with EHE and tactile memory could be located, complicating comparisons with other studies. As mentioned in Chapter 2, Hobbs & Kneller (2009) postulated that the pattern of memory impairment occurs because encoding under narcosis produces a weaker memory trace than normal. According to the information processing model, narcosis disrupts processing when learned material is encoded (Fowler et al., 1985), resulting in fewer cognitive resources being available for encoding. In the current study, participants were also focusing on completing TNT-tt against time, thereby further reducing cognitive resources available for 'memorising'. Thus, the material was learned but the quality of encoding and processing was reduced, producing a weaker memory trace. The time delay before recall (35–40min) would further contribute to the poorer memory. Information encoded at depth also degrades more quickly, and longer delays result in a greater loss of information (Morrison & Zander, 2008).

Learning of material at depth is thus not well preserved upon return to the surface. The findings here may emphasise the importance of other forms of recording of events at depth, to aid memory encoding and subsequent recall at surface.

In order to interpret the findings and compare these to other studies, a note on terminology is required here. As mentioned in Section 4.3.1, the difficulty in accurately naming the memory modality is acknowledged as problematic. Given those difficulties, the term shape memory may be a more accurate term than tactile memory. As noted in Section 5.9, a few participants reported that, during the TNT-dr administration they knew there were only a limited number of basic shapes, and that they thus presented their "delayed recall" responses from "general memory", rather from recently acquired memory. The 8% delayed recall impairment reported here was less than that of other reported studies at comparable depths (20 – 50%, cf. Hobbs & Kneller, 2009; Morrison & Zander, 2008; Philp, et al., 1989; Tetzlaff et al., 1998), which would suggest the possibility of memory skewing results. However, the study was designed so that participants would act as their own controls, and that there would thus be no differential effect of "general memory" between 1 ATA and 6 ATA, and the effect of this potential bias is expected to be equal at both depths.

A number of psychological and biographical variables had significant but very small independent effects on delayed recall after the 6 ATA dive. Divers with higher trait anxiety, divers who were older, and divers who had not completed high school recalled fewer shapes. However, given their very small relative contribution to performance (according to the MRA), the effect of these factors on the performance of individuals during EHE is unclear.

6.1.3. Psychological and biographical variables influencing tactile performance under conditions of experimental hyperbaric exposure

Anxiety

Higher trait anxiety was significantly associated with poorer recall, but with a small effect, while state anxiety was associated with a larger decrement in recall performance. The larger anxiety effects reported in previous studies (e.g. Baddeley & Idzikowski, 1985; Hobbs & Kneller, 2011; Kneller et al., 2012) were not replicated here. This may in part be due to both the sample composition, and the diving environment. Firstly, previous studies generally used sport divers, whereas this study used commercial divers. It is hypothesised that more individuals with high anxiety would self-select out of commercial diving. There is support for this from the present sample, in the form of the small range of anxiety scores, clustered on the lower end of the scales (of both trait and state anxiety measures). Secondly, task administration took place in a low risk hyperbaric chamber environment. The low-threat environment may have removed the anxiety-provoking effect of the open water (Baddeley et al., 1968; Baddeley, 1972).

In general, the limited effect of anxiety on performance in this study may suggest support for the hypothesis that a little anxiety may be beneficial in creating enough arousal to ameliorate the effect of NN, whereas greater anxiety would potentiate its effect. It further supports the position of Hancock & Milner (1986) that anxiety is a less important factor if diver skills and task environment can be controlled (as was the case in this cross-over study in a chamber).

Transient mood states

Fatigue was associated with poorer TNT-tt completion, but its relative contribution to performance (according to the MRA) was very small, and the pre-dive mood state probably did not affect performance during EHE in any meaningful way. However, it is noted that the ranges of the mood scores were very small, and were clustered around the low mood distress point. There were thus no high scores indicating meaningful mood distress, and it is not possible to conclude whether pre-dive (negative) mood states would influence performance.

Subjective experience of narcosis

Subjective experiences played a significant role, and feelings of physical anxiety, representing increased arousal, were associated with better recall. Feelings of cognitive suppression, representing decreased arousal, were associated with a larger decrement in recall performance. While there seems little benefit in using the SHAS composite score, using factor scores appears to add meaning to the interpretation of the results.

Age, gender, and technical competence

No previous evidence was reported that age would play any significant role in moderating the effect of EHE. In the present study, older age was associated with poorer recall and a larger decrement in TNT-tt performance. However, the relative contribution of age to performance (according to the MRA) was very small, and probably does not affect performance during EHE in any meaningful way. As with previous studies (e.g. Jakovljevic et al., 2012), no gender effect of NN on performance was found, although women formed only a small proportion of the sample. The absence of reported evidence that previous technical exposure plays a role in moderating the effects of NN was supported in this study, with no significant effect of technical background observed.

Academic attainment

It has been suggested that greater intellectual ability may protect divers to some extent against the effects of narcosis (Bennett, 1993). The current study may provide some provisional support for this. If academic attainment or development (‘education’) were used as an indicator of general cognitive ability, then lower academic status (i.e. not completed high school) would indicate poorer memory performance. One possible explanation for this phenomenon could be the mechanism of cognitive reserve.

The cognitive reserve hypothesis holds that individuals with greater cognitive abilities are able to delay symptoms of active neuropathology. The emphasis is on the way in which the brain uses its reduced resources, e.g. through the ability to optimise or maximise performance through differential recruitment of brain networks and/or alternative cognitive strategies (Meng & D'Arcy, 2012; Stern, 2002). Education is commonly used as a substitute measure of cognitive reserve (Roe, Mintum, D'Angelo, Xiong, Grant & Morris, 2008). This may imply that individuals with greater cognitive reserves (e.g. more education) could be protected to some extent against the cognitive impairments associated with NN. This hypothesis could be an interesting topic for further study.

An alternative interpretation could be that the significant disparity between further and lesser education on delayed recall was already visible on the surface, and that recall after EHE, while significantly poorer for all, mirrored the pre-morbid performance disparity. The lack of significant difference in the calculated size of disparity between performance at 6 ATA and 1 ATA has been reported earlier. This would suggest that the significantly poorer delayed recall performance of individuals with lesser academic attainment is not an effect of EHE *per se*, but an effect of their pre-morbid ability.

6.1.4. Thematic analysis

The purpose of the thematic analysis was to investigate the use of visual recordings of behaviour during EHE. The analysis found support for the observation of Bennett (2004) that task focus may have a compensatory effect in overcoming, to some extent, the effects of NN. It further found some support for the hypothesis that a failure to follow instructions (without cues) may be an effect of distraction due to the effects of social disinhibition. In this regard, it might be interesting to see whether this could be replicated in future studies, where divers are in the chamber on their own. Finally, the repeated tactile perception of shapes while completing the TNT-tt might be a reminder that even psychomotor tasks have memory components.

Generally, the thematic analysis proved a useful avenue of exploring behavioural manifestations of NN, and might be particularly useful in confirming previous observations and guiding future systematic studies.

6.1.5. Other factors involved in tactile performance under conditions of experimental hyperbaric exposure

Rate of compression

It has been observed that very rapid compression may potentiate narcosis (Bennett, 2004), although this could not be observed in the present study. Although, the range of the speed to reach a pressure of 6 ATA was small, and the three categories were somewhat arbitrary, this variable did not seem to have an effect and was not a confounding variable in the study.

Practice effect

Performance on the surface was a good predictor of performance at depth. This has meaningful implications for the commercial diving industry. The data applies to, among other things, psychomotor skills, which are particularly amenable to practice effects. As effective learning of tasks and skills on the surface can improve completion of those tasks at depth, this emphasises the importance of pre-dive practical learning (‘rehearsal’) as an aid to successful completion of that task. This would be especially true for tasks that are more complex.

Environmental effects

This present study did not use an open-water environment, partly to control for the effects of temperature, protective clothing, and water viscosity when completing a task requiring some manual dexterity. It is recognised that results from dry chambers cannot be transferred directly to open-water conditions (Baddeley, 1966; Baddeley & Flemming, 1967; Baddeley & Idzikowski, 1985; De Moja et al., 1987), and as noted, may partly explain the small effect of anxiety. The hyperbaric effect found in this study would most likely be amplified in an open-water situation.

6.1.6. SHAS

The SHAS showed good psychometric properties, with high internal consistency and three meaningful factors. The association between separate factors and performance provided provisional support to the hypothesis of the role played by increased or decreased arousal in performance under conditions of NN. Administering the SHAS on larger numbers of participants and in the open water may clarify its role in understanding the effects of NN on both objective human performance and subjective experience.

6.2. Methodological issues

6.2.1. Reflection on methods

While the TNT did elicit changes from 1 ATA to 6 ATA, it could be considered that the task itself may have been too easy – as seen in the many full marks (at 1 ATA) – thus limiting the potential size of the differences. The version of the TNT used here, i.e. the number of shapes correctly fitted into the container in 10 min, may not be the most effective way of using the TNT, as it had this ceiling effect. In fact, some participants reached this ceiling before the end of the allocated time (at 1 ATA). Future studies may benefit from using it in its original version, i.e. time to complete the 10 shapes, although it is acknowledged that practical constraints with regard to time limits for decompression may pose a challenge.

In the same vein, while the TNT delayed memory test did elicit changes from 1 ATA to 6 ATA, it is possible that the use of basic, and thus well-known, shapes may have skewed the results. This would apply to the group scores, but not to the difference between 1 and 6 ATA, since each participant was effectively their own control, and the effect of known shapes was maintained in the cross-over design. However, is suggested that novel tasks for testing memory and learning should be used in future studies.

6.2.2. Future directions

Future studies could attempt to replicate the results of tactile perception in open-water conditions, with the added considerations of muscular strain (and associated tactile sensations), buoyancy, water viscosity, and temperature and associated protective clothing.

Investigating possible contributions from the cognitive reserve hypothesis in protecting against the cognitive effects associated with narcosis may prove an interesting avenue of research.

Administering the SHAS under different hyperbaric conditions and with different cognitive or psychomotor tasks, may provide further indications of the association of subjective narcosis on performance and at what pressures this comes into effect. However, larger numbers of participants are required to confirm such a factor analysis.

Lastly, there might be much practical value in exploring the role of tactile and psychomotor practice. For example, the effect of a sample doing two (or more) consecutive ‘blind’ practice runs on the TNT, before following the same procedure as in the current study, might give a good indication of the effect of the amount of practice on possible decrements in performance at depth. This should be done both on land (where practice will generally take place in reality), and in shallow water, to explore the practice effects not only of the number of repetitions, but also of the environment.

Such research would investigate whether or how practice would moderate any effects found in the current study. A control group (not naïve to the task content) could complete the TNT and the delayed recall task under the same experimental conditions as in the present study.

6.3. Implications of the study

6.3.1. Practical

The findings of this study have direct importance for professional divers. This refers to both the commercial diving industry and military applications, where conditions of low visibility occur commonly during deeper diving. Understanding the effect of EHE on tactile perception, and the value of prior exposure, may have important safety and training implications. At the same time, the principles may also apply to recreational diving, for example in safety training and emergency drills, which are in themselves complex tasks, during low visibility dives (like night diving).

In particular, complex neuropsychological tasks requiring tactile inputs were impaired by 9.5% at 6 ATA in a chamber; presumably, they would be impaired even more significantly in the open water. To compensate for this, divers would benefit by firstly planning more time to complete complex tasks, and secondly by practicing those tasks prior to the actual deep dive (either on the surface or in shallow water).

Further, tasks requiring memory were impaired by 8% after dives to 6 ATA in a chamber; presumably, they would be impaired even more significantly in the open water. The finding that encoding tactile stimuli at depth is not well preserved upon return to the surface emphasises the importance of utilising other forms of recording of events or objects at depth, to aid memory encoding and subsequent recall at surface.

6.3.2. Theoretical

As mentioned, the poorer TNT performance under conditions of NN could support the slowed information processing model. The complex nature of the task makes it particularly susceptible to the cumulative effects of slowed information processing. The role of arousal in mediating this effect also found support from the subjective reports of participants, where feelings of physical anxiety, representing increased arousal, were associated with better recall, while feelings of cognitive suppression, representing decreased arousal, were associated with a larger decrement in recall performance.

Previous research (Petri, 2003) has observed changes in strategies of solving psychological tests under hyperbaric conditions, and in this regard, the role of cognitive reserve in mitigating the effects of narcosis needs further exploration. In particular, it may explain the inter-individual variability in performance; it may further provide a model to investigate the possible effects of activating alternative cognitive strategies and their mechanisms. This is closely related to the third feature of the slowed information processing model, namely strategic variables.

As referred to previously, the poorer recall after the deep dive could be regarded as support for the model of Hobbs & Kneller (2009), namely, that the pattern of memory impairment occurs because encoding under narcosis produces a weaker memory trace than normal. The high cognitive demand task (TNT-tt) at depth further reduced cognitive resources available for encoding (by reducing rehearsal capacity), producing a weaker memory trace.

6.4. Conclusion

The purpose of this study was to investigate certain neuropsychological aspects of NN, with special reference to tactile perception and memory, and to examine the relationships of tactile performance with other psychological and biographical factors. In this regard, all the set objectives were met, and evidence of impairment of neuropsychological functions under conditions of NN was indeed found.

In conclusion, the findings of this study have important practical implications for professional divers in both the commercial diving industry and in military applications, where conditions of low visibility occur during deep diving.

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ADDENDA

Addendum A: Participant Information and Consent Form

Addendum B: Biographical Questionnaire

Addendum C: Trait Anxiety Scale

Addendum D: Brunel Mood State Scale

Addendum E: Subjective High Assessment Scale

ADDENDUM A: PARTICIPANT INFORMATION LEAFLET AND CONSENT FORM

TITLE OF THE STUDY:	"A prospective cross-over study investigating specific aspects of neuropsychological performance in hyperbaric environment"
REFERENCE NUMBER:	N11/06/176
PRINCIPAL INVESTIGATOR:	Dr Charles van Wijk
ADDRESS:	P O Box 494 Simon's Town 7995
CONTACT NUMBER:	084 771 9432 chvanwijk@gmail.com

You are being invited to take part in a research project. Please take some time to read the information presented here, which will explain the details of this project. Please ask the study staff or doctor any questions about any part of this project that you do not fully understand. It is very important that you are fully satisfied that you clearly understand what this research entails and how you could be involved. Also, your participation is **entirely voluntary** and you are free to decline to participate. If you say no, this will not affect you negatively in any way whatsoever. You are also free to withdraw from the study at any point, even if you do agree to take part at the beginning.

This study has been approved by the **Committee for Human Research at Stellenbosch University** and will be conducted according to the ethical guidelines and principles of the international Declaration of Helsinki, South African Guidelines for Good Clinical Practice and the Medical Research Council's Ethical Guidelines for Research.

What is this research study all about?

This study looks at the effect of high pressure (e.g. when diving) on certain brain functions, in particular your tactile perception ("sense of touch"), as well as certain other factors that might influence this effect (e.g. your age or education, water temperature, etc.).

During your participation, you will complete a questionnaire about your personal background on entry into the study, and then twice during your diving training program you will complete a mood checklist and a practical task (using your hands, to measure your sense of touch). You will do this once at 1 ATA, and once in a chamber at a pressure of 6 ATA.

The order in which you will do this (1 ATA or 6 ATA) will be determined by chance. You will do the practical task 'blindfolded', in other words while wearing a blackened out mask, in order for you to rely on your sense of touch, and not you vision. For this reason, you will also not see the task beforehand, but will receive a thorough briefing on what to do before you start.

Your participation will take place during the course of your diving training program here at the diving school. We aim to include as many students as possible. In order to get the most reliable measurements, we ask that you do not discuss the blindfolded task with your fellow students until the end of the study.

Why have you been invited to participate?

All students at this diving school who will be diving to 50m in a chamber during their commercial diving training are invited.

What will your responsibilities be?

You will complete an entry biographical questionnaire, and then twice during your course, complete a mood checklist and a practical task. The task takes on average about 15 minutes to complete.

Will you benefit from taking part in this research?

The benefit from this study will be for the broader diving medical community, who will use the information to make better decisions on fitness to dive, as well as better input into safety and training practices for divers.

If you would like individual feedback regarding your own performance during the completion of the two tasks, you are welcome to contact the principal investigator to arrange for this.

Are there any risks involved in your taking part in this research?

No. There might be some discomfort completing the tasks with a blackened mask, but the effect would be the same as diving in zero visibility.

Who will have access to your records?

Your personal information, as well as the mood checklists, is considered confidential, and after you complete them, you will place them into an envelope and seal it. The measurements from your practical task will also be sealed into envelopes. These envelopes will only be opened by the principal researcher, and all records will be kept confidential and protected as such. Other researchers will only have access to the anonymous data, in other words with your name removed from it, to protect your privacy. In the same way, if any of the information is used in any reports or other publications, it will be used anonymously. The health research ethics committee members or other study monitors may look at study data to ensure that you are treated correctly in this study and that you are not put at risk.

Will you be paid to take part in this study and are there any costs involved?

No. you will not be paid to take part in the study – it will be incorporated into your diving training program. There will be no costs involved for you, if you do take part.

Is there anything else that you should know or do?

- You can contact Dr Charles van Wijk at tel 084 771 9432 or at chvanwijk@gmail.com if you have any further queries or encounter any problems.
- You can contact the Committee for Human Research at 021-938 9207 if you have any concerns or complaints that have not been adequately addressed by your study doctor.
- You will receive a copy of this information and consent form for your own records.

Declaration by participant

By signing below, I ……………………………………………….………… agree to take part in a research study entitled *“A prospective cross-over study investigating specific aspects of neuropsychological performance in hyperbaric environments”*

I declare that:

- I have read or had read to me this information and consent form, and it is written in a language with which I am fluent and comfortable.
- I have had a chance to ask questions and all my questions have been adequately answered.
- I understand that taking part in this study is **voluntary** and I have not been pressurised to take part.
- I may choose to leave the study at any time and will not be penalised or prejudiced in any way.
- I may be asked to leave the study before it has finished, if the study doctor or researcher feels it is in my best interests, or if I do not follow the study plan, as agreed to.

Signed at (*place*) ....…........……………. on (*date*) …………....……….. 2013.

... **...**
Signature of participant Signature of witness

Declaration by investigator

I *(name)* ……………………………………………..……… declare that:

- I explained the information in this document to ………………………………..
- I encouraged him/her to ask questions and took adequate time to answer them.
- I am satisfied that he/she adequately understands all aspects of the research, as discussed above.
- I did not use an interpreter.

Signed at (*place*) ....…........……………. on (*date*) …………....……….. 2013.

... **...**
Signature of investigator Signature of witness

ADDENDUM B: BIOGRAPHICAL QUESTIONNAIRE

1. Name: ....

2. Identity/passport Number: ....

3. Date of birth and current age: ....

4. Gender: ....

5. Contact details: ....

6. Education:

   Please list all your qualifications:

Academic qualifications	
Technical qualifications	
Diving qualifications	
Total amount of hours breathing compressed air (±)	

7. Technical background:

a. Please list all other technical exposure you've had (for example working in engineering jobs, personal hobbies, etc.)

....

....

b. Please grade your technical competency (how good you are) on a scale from 1 to 10: (please circle your choice):

1	2	3	4	5	6	7	8	9	10
(not good)								(very good)	

8. Medical history:

a. Have you had any previous head injury resulting in temporary unconsciousness? If yes, please give details (e.g. what, when, outcome):

....

b. Have you previously had any serious illness? If yes, please give details (e.g. what, when, outcome):

....

c. Have you in the past ever suffered from, or received treatment for, any of the following conditions? If yes, please give details (e.g. when, for how long, treatment, your current status, etc.):

* serious diving accidents or mishaps

....

* claustrophobic reactions

....

* alcohol abuse

....

* other substance abuse

....

* depression

....

* anxiety

....

d. Please complete the attached scale (on the next page) that asks about at your personal disposition. It is very important that you complete it honestly. Then fold the document and place it in the envelope provided.

ADDENDUM C: TRAIT ANXIETY SCALE

A number of statements, which people have used to describe themselves, are given below. Read each statement and then select (circle) the appropriate value to the right of the statement to indicate HOW YOU GENERALLY FEEL. There are no right or wrong answers. Do not spend too much time on any one statement, but choose which seems to describe how you generally feel.

1 - Almost Never 2 - Sometimes 3 - Often 4 - Almost Always

1	I am a steady person.	1	2	3	4	___
2	I feel satisfied with myself.	1	2	3	4	___
3	I get in a state of tension or turmoil as I think over my recent concerns and interests.	1	2	3	4	___
4	I wish I could be as happy as others seem to be.	1	2	3	4	___
5	I feel like a failure.	1	2	3	4	___
6	I feel nervous and restless.	1	2	3	4	___
7	I feel secure.	1	2	3	4	___
8	I lack self-confidence.	1	2	3	4	___
9	I feel inadequate.	1	2	3	4	___
10	I worry too much over something that really does not matter.	1	2	3	4	___

Thank you!

ADDENDUM D: BRUNEL MOOD STATE SCALE

BRUMS CHECKLIST

1.	Name:		
2.	Identification number:		
3.	Date		
4.	Completing checklist:	First time	Second time

Below is a list of words that describe feelings people have. Please read each one carefully, then cross the number that best describes HOW YOU FEEL RIGHT NOW. Be sure to complete every item.

	FEELING	Not at all	A little	Moderately	Quite a bit	Extremely
1	Panicky	0	1	2	3	4
2	Lively	0	1	2	3	4
3	Confused	0	1	2	3	4
4	Worn out	0	1	2	3	4
5	Depressed	0	1	2	3	4
6	Downhearted	0	1	2	3	4
7	Annoyed	0	1	2	3	4
8	Exhausted	0	1	2	3	4
9	Mixed-up	0	1	2	3	4
10	Sleepy	0	1	2	3	4
11	Bitter	0	1	2	3	4
12	Unhappy	0	1	2	3	4
13	Anxious	0	1	2	3	4
14	Worried	0	1	2	3	4
15	Energetic	0	1	2	3	4
16	Miserable	0	1	2	3	4
17	Muddled	0	1	2	3	4
18	Nervous	0	1	2	3	4
19	Angry	0	1	2	3	4
20	Active	0	1	2	3	4
21	Tired	0	1	2	3	4
22	Bad tempered	0	1	2	3	4
23	Alert	0	1	2	3	4
24	Uncertain	0	1	2	3	4

T	D	A	V	F	C	TMD

ADDENDUM E: SUBJECTIVE HIGH ASSESSMENT SCALE

PERSONAL EXPERIENCE SCALE

Below is a list of adjectives which describes subjective feelings.

Please rate each adjective, as to **how you feel at this moment**, on a scale from 0 to 10, where: 0 = not at all, 5 = moderately, 10 = extremely. You need to write the number you choose (ANY number between 0 and 10) in the space provided.

	0 = not at all 5 = moderately 10 = extremely
High	
Anxious	
Confused	
Elated	
Dizzy	
Nauseous	
Uncomfortable	
Light-headed	
Weak	
Tense	
Intoxicated	
Difficulty concentrating	

Name:		
Identification number:		
Date		
Completing checklist:	First time	Second time