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# Inert gas narcosis disrupts encoding but not retrieval of long term memory

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## HIGHLIGHTS

- Free-recall memory significantly impaired only when words were initially learned at high pressure.
- Free recall not impaired when words learnt at low pressure and then recalled at low or high pressure.
- Deeper processing failed to significantly improve free-recall ability across each condition.
- Pattern of results support hypothesis that narcosis disrupts encoding of information, not retrieval.

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## ABSTRACT

Exposure to increased ambient pressure causes inert gas narcosis of which one symptom is long-term memory (LTM) impairment. Narcosis is posited to impair LTM by disrupting information encoding, retrieval (self-guided search), or both. The effect of narcosis on the encoding and retrieval of LTM was investigated by testing the effect of learning–recall pressure and levels of processing (LoP) on the free-recall of word lists in divers underwater. All participants ($n = 60$) took part in four conditions in which words were learnt and then recalled at either low pressure (1.4–1.9 atm/4–9 msw) or high pressure (4.4–5.0 atm/34–40 msw), as manipulated by changes in depth underwater: low–low (LL), low–high(LH), high–high (HH), and high–low (HL). In addition, participants were assigned to either a deep or shallow processing condition, using LoP methodology. Free-recall memory ability was significantly impaired only when words were initially learned at high pressure (HH & HL conditions). When words were learned at low pressure and then recalled at low pressure (LL condition) or high pressure (LH condition) free-recall was not impaired. Although numerically superior in several conditions, deeper processing failed to significantly improve free-recall ability in any of the learning–recall conditions. This pattern of results support the hypothesis that narcosis disrupts encoding of information into LTM, while retrieval appears to be unaffected. These findings are discussed in relation to similar effects reported by some memory impairing drugs and the practical implications for workers in pressurised environments.



## 1. Introduction

Human memory is composed of a hypothetical set of cognitive structures and processes proposed to have direct neural correlates in the brain [1]. Pharmacological interference with these neural correlates will directly impact memory performance selectively, according to which brain regions or systems are affected [2]. One such pharmacological phenomenon is inert gas narcosis which causes memory loss when individuals are exposed to increased ambient pressure [3]. At pressures greater than 4 atmospheres (atm)/30 metres of sea water (msw) inert gas molecules absorbed into the body via breathing mixtures interfere with neural transmission [4] to an extent that performance impairments on a number of tasks are measurable. Numerous studies have demonstrated that at pressures of 4–6 atm (30–50 msw) both the delayed free- and cued-recall of wordlists are impaired compared to surface or low pressure controls [5–14]. It was initially suggested that this indicated narcosis prevents the input of information into long-term memory (LTM) [10]. However, when delayed recognition tests are employed, also a measure of LTM, this impairment does not occur [7,10,15]. This contradictory effect of narcosis on different measures of LTM suggest a more nuanced effect of narcosis on memory which is potentially explained in one of three ways: 1) narcosis disrupts retrieval of LTM; 2) narcosis disrupts encoding into LTM; and 3) narcosis affects both retrieval and encoding of LTM.

In the first (retrieval) explanation, information is stored in LTM but impairment of self-guided search by narcosis means the information is harder to retrieve. The discrepancy between the free-recall and recognition measures is explained as resulting from the cues provided during the recognition test reducing the need for self-guided search [10].

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However, data from two studies [8,10] places doubt on the self-guided search theory. These studies reported an impairment of free-recall only when information was learned at high ambient pressure (i.e. under narcosis) and either recalled at high or low pressure (no narcosis). When information was learned at low pressure and recalled under narcosis no impairment was found and retrieval appeared to be unaffected [10]. This suggested that narcosis interfered with the input of new information into LTM when it was initially encoded, rather than in retrieval. Thus, according to the second, encoding explanation material can still be learned but the quality of the encoding process is reduced, leading to a weaker memory trace. In a recognition test the cues provided make retrieval less demanding than self-guided search [16] and hence a weaker memory trace is sufficient for successful recognition. The encoding explanation has also been investigated using the levels of processing (LoP) approach [17] which claims the durability of memory is dependent on the depth of processing the stimulus undergoes when it is initially encoded. In two studies, Kneller and Hobbs [11,12] compared the LoP effect underwater at narcotic pressures with a shallow water control but the results were inconclusive. In one study [11] deeper processing improved recall under narcosis lending support for the encoding hypothesis but in the second study [12] recall was not improved by deeper processing under narcosis indicating support that narcosis affects self-guided search.

The third explanation is based on the slowed processing model of narcosis [18,19]. In this model task performance is impaired because narcosis acts as a depressant on the central nervous system, reducing efficiency, rather than acting in a more targeted way by disrupting particular cognitive structures. The depressant effects of narcosis slow down the cognitive system as a whole, predicting that both self-guided search and encoding will both be affected by narcosis. At present there is little data to support this contention, except that by Fowler et al [20,21] who reported that during a memory task the rate of rehearsal during the encoding process and response time was slowed by narcosis.

The existing studies of narcosis and memory provide an inconclusive set of data with some support found for all three of the above explanations. These studies might be reconciled by combining the learning–recall and LoP methodologies into one experiment, providing data comparing the LoP effect while concurrently manipulating the presence or absence of narcosis at either encoding or during self-guided search. This can disentangle the effects of narcosis on both self-guided search and encoding. The current study did this by testing free-recall memory ability when words were learned and recalled at either high (H) or low (L) ambient pressure. Participants learned and recalled words in four combinations: low pressure to low pressure (LL); low pressure to high pressure (LH); high pressure to high pressure (HH); and high pressure to low pressure (HL). In addition, half the participants encoded the words using shallow processing and half using deep processing. The explanations outlined above predict three potential outcomes: 1) Encoding affected: impairment from narcosis will only be present when words are learned at high pressure (HH & HL conditions), not when learned at low pressure (LL & LH). Deep processing will improve recall over shallow processing in all conditions, but some impairment from narcosis will remain. 2) Retrieval affected: impairment from narcosis will only be present when words are recalled at high pressure (LH & HH), not when recalled at low pressure (HL & LL). Deeper processing will improve recall only when recall takes place at low pressure (HL & LL) and not at high pressure (LH & HH). 3) Encoding and retrieval affected: recall will be the lowest when both learning and recall takes place at high pressure (HH) under narcosis. Recall will be the highest when learning and recalled takes place at low pressure in the absence of narcosis (LL), with the LH and HL conditions falling somewhere in between. Improved recall from deeper processing will be extinguished, or severely diminished, in the HH condition and reduced in the LH and HL conditions. At present prior evidence seems to favour the first prediction. Thus, in the current study it was hypothesised that free-recall performance would be affected by narcosis in a pattern that reflected an impairment during the encoding of memory.

## 2. Method

### 2.1. Design

The study employed a $4 \times 2$ mixed design comparing the effects of a within participants variable of learning and recall pressure [low–low (LL) vs. low–high (LH) vs. high–low (HL) vs. high–high (HH)] and a between participants variable of LoP (shallow vs. deep) on free recall performance. Narcosis was manipulated by testing in shallow water where narcosis is not considered to be present in the low pressure conditions (1.4 atm to 1.9 atm/4–9 msw) and in deep water at depths considered narcotic in the high pressure conditions (4.4 atm–5.0 atm/34–40 msw). The degree of narcosis in the high pressure conditions was maintained by only testing at ocean depths in the narrow range between 34 and 40 msw. At low pressure participants were tested at 1.4 atm to 1.9 atm (4–9 msw) and at high pressure at 4.4 atm–5.0 atm (34–40 msw). The order of the pressure conditions was counterbalanced across four combinations so that order effects could be tested for: 1) HH–LL–LH–HL; 2) HL–LL–LH–HH; 3) LL–HH–LH–HL; and 4) LL–LH–HH–HL.

### 2.2. Participants

The protocol was approved by the ethics committee of the University of Winchester. Sixty divers volunteered for the study, with 30 assigned to each processing condition. All participants were customers and staff of the recreational dive operation West Bay Divers on Roatan Island, Honduras. West Bay Divers screened participants to ensure they were medically fit and suitably qualified to dive to the depths required for the study. Participants who were not qualified to PADI Deep Diver Specialty (or equivalent) or unwilling to do this course before taking part in the study were not admitted. Participants over the age of 52 years were not admitted to the study because of the detrimental effects of older age on memory ability [22]. In order to allow sufficient numbers of divers to be recruited, volunteers with a range of experience levels were recruited. The experience level of the divers ranged from PADI Deep Diver (or equivalent) certification up to Instructor level certifications. Participants self-reported to the researchers how many dives they had completed and how many years it was since they had started diving as a measure of general diving experience.

### 2.3. Measures and materials

Five word lists of 10 target words each were formulated for the free recall task. The target words were chosen using the MRC Linguistic Database v2.0. Target words were between four and six letters long, with a maximum number of 2 syllables (e.g. mash; rebel; empire). All target words were matched for familiarity, concreteness, and imageability. All wordlists consisted of different target words. One wordlist was only used when participants were tested on the surface during the practice session. The other four lists (labelled A to D) were used underwater and counterbalanced across the conditions to control for order effects. Each target word was printed on paper and laminated into a card (font size 19, Times New Roman). Above each target word was printed a sentence which varied according to the processing condition. In the shallow processing condition the sentence was either: “Is the word in lower case letters?” or “Is the word in upper case letters?”. The target word below was printed in either lower case or uppercase letters. The participant was required to answer the question with a yes/no response. There were an equal number of lower and upper case questions, and an equal number of target words in upper and lower with an equal number of yes/no correct responses, in each list. In the deep processing condition varying sentences were printed with a word missing (e.g. “The cat___up the tree"). The target word below either made sense as part of this sentence or did not. Participants were required to respond with a 'yes' if the target word made sense as part of the sentence or 'no' if the target work did not. There were an equal number of possible yes/no responses in each wordlist.

All dives were conducted using air (21% Oxygen; 79% Nitrogen) from the shore or from a boat, depending on the logistical arrangements of the dive operation each day. Participants wore full dive equipment in the water (3 mm 'shorty' wetsuit, weights, buoyancy control device, mask, and fins) and used either 12 or 15 l air tanks. Depths on each dive were measured using a Cressi Leonardo 2 dive computer, worn by the researcher and held at chest height. On selected dives, at the researcher's discretion, a PADI Divemaster was assigned as a safety support diver to accompany the researcher and participants underwater (e.g. if two participants were considered relatively inexperienced divers). Supporting Divemasters positioned themselves out of sight, behind the participants, when testing was taking place in order to avoid distraction to the participants when engaged in the task.

### 2.4. Procedure

Participants first completed a practice session on the surface. In this session participants were presented with one of the wordlists. Each target word was presented for 5 s. In response to each target word participants wrote down their yes/no response on a piece of paper. Once all 10 words had been presented and responses given there was a break of 3 min. Participants were then instructed to write down as many of the target words that they could remember, in any order. The number of words correctly recalled constituted the free recall test score.

Once the practice session was complete participants were briefed on the protocol for the underwater sessions. All underwater sessions were conducted at a site named Mandy's Eel Garden, close to the shore off West Bay Beach on the island of Roatan in Honduras. The site consisted of a flat sandy lagoon at a depth of 2–10 msw. The low pressure segments of testing took place in this lagoon. A break in the reef led to a reef wall that ended at a deeper sandy plateau situated at a depth of 30–45 msw, where the high pressure segment of testing took place each time. Ocean conditions were very consistent with little or no current, clear visibility between 15 and 30 m, temperatures of 27–28 °C. Conditions in this part of the Caribbean are such that there is a very little difference in overall brightness across the depths used in this study.

Testing took place over the course of two dives, with two learning–recall pressure conditions completed on each dive. It was not possible to conduct separate dives for each learning–recall condition because of financial constraints. The order of the pressure conditions was counterbalanced over the four combinations in the interests of safety, as it would not have been possible to conduct every possible combination. For example, it would have been unsafe to have conducted the HH condition, followed by the LH condition on the same dive because swimming between deep water, shallow water, and then back to deep water, would have made the risks of decompression sickness and the threat of a low on air situation unacceptable. A maximum of two participants were allowed to take part in the study on each dive in order to maximize safety and smooth running of the protocol.

The general protocol for the free-recall task was the same as on the surface. For the LL and HH conditions participants were led (maximum two participants at one time) to the required depth and given time to get comfortable and kneel on the ocean floor. They were then presented with the words (learning phase) and recorded their responses on an underwater slate. Once word presentation was complete the researcher took away the slate and the participants swam slowly along the ocean floor at the same depth for 3 min. Participants were instructed to swim in order to mimic the swimming necessary in the LH and HL conditions, outlined below. Just before the end of the 3 min the participants were instructed to kneel on the ocean floor again and at the three minute mark handed back another slate on which they wrote down (recall phase) as many of the target words as they could remember. They were given a maximum of 1.5 min to write these down. These times were set out so that the task could be safely completed within the no decompression limit at 40 msw. The protocol in the LH and HL conditions was the same except in the break between word presentation and recall participants ascended and descended to the required depths. In the LH and HL conditions the break between learning and recall could not be precisely controlled. This was because not every participant could not ascend and descend at exactly the same rate because of factors such as swimming speed and ability to equalize during descent. It was also important to make the transition between depths as comfortable and relaxed as possible both for safety and to avoid issues of anxiety or exertion that might distract participants from the task. The result was breaks between learning and recall of 3 min and six minute learning and recall for the LH and HL conditions, the implications of which are discussed in Section 3.

### 2.5. Data reduction and analysis

Mean recall score was calculated for each learning–recall pressure condition. The surface data was excluded because it was considered a practice session, not of prime importance to the study, and because the surface session had not been counterbalanced with the underwater conditions. The data was tested for significance using Analysis of Variance (ANOVA) with an alpha value of .05 taken as the criterion of significance. The data was first tested for effects of dive experience, age, gender, and counterbalancing groups. Mean experience levels did not differ significantly between the processing conditions based on number of dives, $t(58) = 0.64$, p = .53, or years of diving, $t(58) = 1.2$, $p = .24$, and had no effect on recall. Mean age in the deep processing condition was significantly lower compared to the shallow processing condition, $t(58) = 2.46$, p = .02, but when age was added in the analysis as a covariate no significant age related effects were found on recall. Nor were any significant effects of gender and counterbalancing group on recall found (all *ps* > .05). For this reason age, gender, dive experience and counterbalancing group are excluded from the results below and are not discussed further. The data below represents the results of a 4 × 2 mixed ANOVA testing for the effects of learning–recall pressure and LoP condition. Post hoc analysis was conducted using follow-up *t*-tests with a Bonferroni adjustment.

## 3. Results

### 3.1. Effect of learning–recall pressure

Participant demographics are displayed in Table 1. Fig. 1 shows the mean recall scores for each of the learning–recall pressure conditions. There was a clear split in recall between those conditions where learning took place at low pressure and those conditions where learning took place at high pressure. Recall in the HH ($M = 3.7$; $SD = 1.7$) and HL ($M = 3.6$; $SD = 1.7$) conditions were comparable to each other but were lower than in the LL ($M = 4.8$; $SD = 1.5$) and LH ($M = 4.6$; $SD = 1.4$) conditions. The results of the ANOVA revealed a significant effect of learning–recall condition on mean recall, $F(3, 174) = 17.6$, $p < .001$. The results of the Post Hoc *t*-tests are displayed in Table 2. They revealed that mean recall differed between every condition, except between the LL and LH conditions, and the HH and HL conditions. The clear indication is that narcosis only impaired free recall

**Table 1**
Key participant characteristics for each processing condition and entire sample.

| | N | Males/ females | Age range (years) | Mean age (+SD) | Dives (+SD) | Years of diving |
|---|---|---|---|---|---|---|
| Entire sample | 60 | 30/30 | 18–52 | 33.5 (8.9) | 359.6 (822.0) | 8.5 (7.0) |
| Shallow | 30 | 15/15 | 18–52 | 36.2 (9.2) | 427.6 (999.6) | 9.6 (8.3) |
| Deep | 30 | 15/15 | 21–51 | 30.8 (7.7) | 291.7 (604.9) | 7.4 (8.0) |

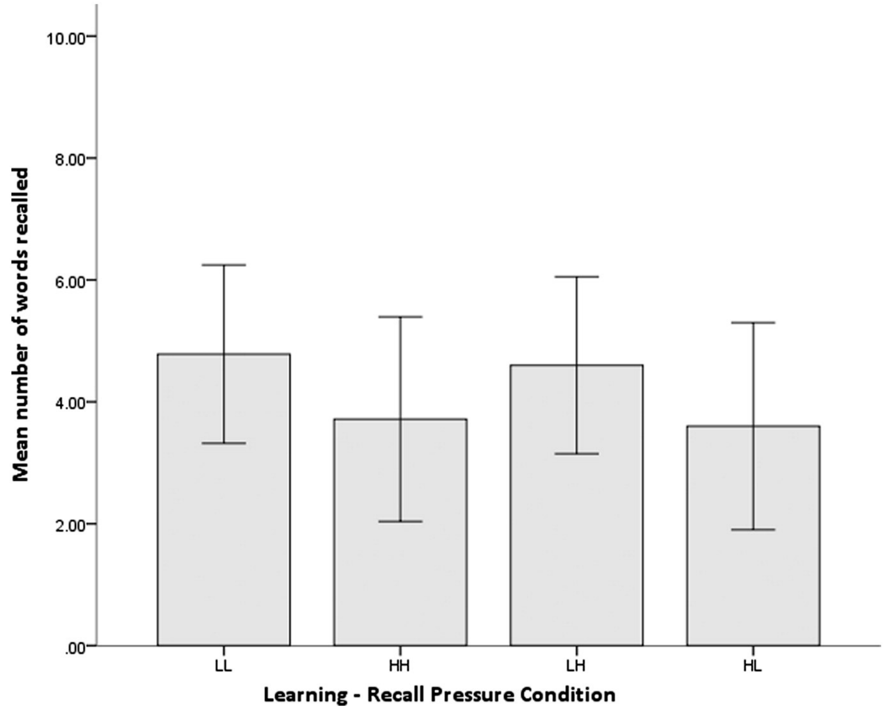


**Fig. 1.** Mean (+SD) free-recall score for learning–recall conditions.

performance when information was learned at high pressure, regardless of the pressure at which was recall took place.

### 3.2. Effect of levels of processing

Mean recall scores for LoP conditions across the learning–recall pressure conditions are displayed in Table 3. In the LL condition recall was almost identical for the shallow and deep processing conditions and there was no discernible LoP effect. In the HH and LH conditions recall was greater in the deep processing than in the shallow processing condition, as predicted, but in the HL condition it was slightly lower. These means suggest that deeper processing increased recall in the HH and HL conditions but not the LL and LH conditions. However, the 4 × 2 ANOVA revealed that there was no significant main effect of LoP, $F(1, 58) = 0.603$, $p = .440$, and no LoP × learning–recall pressure condition interaction, $F(3, 174) = 1.92$, $p = .128$.

## 4. Discussion

It was stated previously that narcosis may affect LTM ability in one of three possible ways: 1) by impairing the encoding of information when it is initially learned; 2) by impairing retrieval of information from LTM; 3) by affecting both the encoding and retrieval of information. Comparison of free-recall performance across learning–recall conditions demonstrated that recall is only impaired when information is initially learned at pressures of 4.4–5.0 atm, regardless of whether recall takes place at the same or lower pressures of 1.4–1.9 atm. Recall of information that is learned at pressures of 1.4–1.9 atm is not impaired, even when recall takes place at higher pressures between 4.4 atm and 5.0 atm. This pattern of results replicate, with a far larger sample, those of Tetzlaff et al [8] and Hobbs & Kneller [10] and support the first prediction that narcosis affects the encoding of information into LTM. These results do not support the second prediction that narcosis affects self-guided search as recall was not impaired when words were learned at low pressure and recalled at high pressure but were impaired when learned at high pressure and recalled at low pressure. The third prediction from the slowed processing theory that both encoding and retrieval are affected was also not supported. If this were the case the LL condition should have had significantly higher recall than the other three learning–recall conditions. As the LL was not significantly different from the LH condition the pattern of results better fits the theory that narcosis affects the encoding of information into LTM.

One factor in the learning–recall data that deserves consideration is that it was not possible to control the length of the delay between learning and recall phases in the LH and HL conditions because of the need to ascend or descend to the required recall depth. The delay between learning and recall in the HH and LL conditions was always 3 min but in the LH and HL conditions it varied between 4 and 6 min. Though this could not be avoided, there is concern that recall scores in the LH and HL may simply have reflected differences in the delay rather than of narcosis. Longer delays could have negatively affected recall through forgetting or improved recall because a participant had more rehearsal time. However, the authors contend that these differences in delay did not adversely affect the findings. In the first instance, when the delay was controlled in the LL and HH conditions there was a clear

**Table 2**
Results of Post Hoc t-tests comparing differences between learning and recall pressure conditions.

| Condition | df | t value | P value |
|---|---|---|---|
| LL vs. HH | 59 | 4.76 | <.01 |
| LL vs. LH | 59 | 0.96 | .34 |
| LL vs. HL | 59 | 5.69 | <.01 |
| HH vs. LH | 59 | 4.92 | <.01 |
| HH vs. HL | 59 | 0.52 | .61 |
| LH vs. HL | 59 | 5.07 | <.01 |

**Table 3**
Mean (+SD) words recalled in learning–recall and LoP conditions and interval (seconds) between learning and then recall.

| Condition | Recall shallow processing | Recall deep processing | Learning–recall interval |
|---|---|---|---|
| L–L | 4.8 (1.4) | 4.8 (1.5) | 180 (0) |
| H–H | 3.4 (1.5) | 4.0 (1.8) | 180 (0) |
| L–H | 4.3 (1.1) | 4.9 (1.7) | 234 (42) |
| H–L | 3.7 (1.4) | 3.5 (2.0) | 258 (40) |

impact of narcosis on recall. Secondly, mean delay in the LH condition ($M = 3.91$ min; $SD = 0.7$) was similar to that in the HL condition ($M = 4.31$ min; $SD = 0.7$). This amounts to a mean difference between the LH and HL conditions of just 24 s. Prior research has reported that comparisons of similar variations in length of delay between learning and recall have no impact on free-recall. For example, Madigan and Lawrence [23] reported that free-recall of word lists was the same whether the delay between learning and recall was 5 or 15 min.

Taken alone the learning–recall data appear to provide clear evidence of a sole effect of narcosis on encoding. The LoP data aimed to build upon this in light of previous LoP results giving contradictory conclusions as to whether narcosis affects encoding or self-guided search [11,12]. Unfortunately there was a failure to obtain the LoP effect in any of the learning–recall pressure conditions and it was not possible to consider this data in relation to the predictions made.

The failure to find an LoP effect reflects either some fault of the methodology used in this study or, we propose, is an attribute of the underwater environment used. The effect of narcosis on memory at the pressures divers were exposed to in this study was small, with a typical mean reduction of just one word or 10%. Recall in other underwater studies at similar pressures has also reported to be small [10], as were any improvements provided by deeper processing in the previous LoP studies [11,12]. While the underwater environment replicates the conditions where narcosis is most often experienced and can clearly be used to measure the effect of narcosis on behaviour, it brings a certain amount of general distraction and additional attentional demands compared to other environments, such as the hyperbaric chamber. Given the small effects being measured and the additional demands of the underwater environment, any small LoP effects could have been obscured. This might explain the contradictory nature of the LoP findings in previous studies [11,12] where the effect was not particularly robust and yielded contradictory conclusions on whether encoding or self-guided search was affected. A future study may seek to replicate the current data with an even larger sample or in a hyperbaric chamber where there are less attentional demands.

Other methodological concerns are any potential role of stress caused by the underwater environment and the concerns about controlling the ‘dose’ or level of narcosis in an underwater environment. Stressful changes in water temperature have been shown to affect memory performance [24] and increased state anxiety underwater has been reported to potentially magnify impairment from narcosis [25,26]. Furthermore, an interaction between stress hormones and memory formation under anaesthesia, considered similar to narcosis, has previously been reported [27]. Physical environmental stressors are unlikely to have affected the results as the location for the current study was chosen because of its excellent ocean conditions with excellent swimming pool-like visibility, warm temperatures, and minimal surge and current. Temperature conditions between the pressure conditions were very similar with little difference in temperature (at most 1 °C) from 2 msw to 40 msw. Participants were screened so that only those that were comfortable in the conditions could take part in the study but fluctuations in state anxiety could have occurred while underwater across conditions and should be noted as potential limitation of this study. Concerns about the level of narcosis experienced by participants rest on the fact that there is currently no direct physiological measure of narcosis available equivalent, for example, to a blood alcohol test for alcohol. The current study attempted to control the level of narcosis, which is determined by ambient pressure, by only testing at a narrow pressure range (34–40 msw/4.4–5.0 atm). However, the level of narcosis may have differed across participants according to individual differences. The nature of these individual differences are unknown, or remain contested, but it is important to note that in this study a limiting factor is that it was impossible to determine whether all participants were experiencing the same level of narcosis.

In support of our findings that memory impairment experienced under narcosis is driven by a detrimental effect of encoding into LTM, it is worth noting that some other memory impairing agents have also been argued to cause impairment by primarily affecting encoding [28–30]. For example, anaesthetics are well known to have a negative impact on memory [31,32]. Recall of information encoded under anaesthesia and recalled when fully conscious is impaired [33] and thus may operate in a similar way to narcosis. As has been found with narcosis, alcohol [34–37] has been shown to reliably impair the free-recall of word lists whereas impairment of recognition memory is less consistent [36,38,39]. The same has been reported of ketamine [40,41] and cannabis [42]. There are instances in the alcohol literature that exactly mirror the findings of the current study. For example, both Jones [34] and Birnbaum et al. [35] reported that free-recall was impaired when learning took place under the effects of alcohol, which equates to the current finding that narcosis impaired performance in the HH condition. However, when words were learned in a sober state and recalled either under the effects of alcohol or when sober, recall was unaffected. This pattern of results equate with the findings that recall was not impaired in the current study in the LH and LL conditions. While acknowledging that narcosis and these drugs have a broadly different pharmacological action in the brain, noting such similarities can be useful as they suggest interference with the same cognitive systems, hint at shared neural underpinnings, and could be used to target treatments for relieving or managing memory impairment. Indeed, memory studies investigating such phenomena have been integral for developing and confirming theoretical models of memory [e.g. 43].

For this reason further consideration and research into the commonalities of the effects of narcosis and drugs could be highly relevant to understanding how narcosis affects cognition and operates at the neurobiological level, and vice versa. Ultimately, this may provide methods to eliminate or reduce narcotic impairment using pharmacological agents. For example, Nutt et al. [37] reported that impairment of free-recall by alcohol was almost completely eliminated by pretreatment of a benzodiazepine receptor inverse agonist. If alcohol and narcosis impair memory in similar ways, as commonality in their effects suggest, then the same or similar agent may also eliminate memory impairment under narcosis.

The current study and, to our knowledge, all other studies of memory impairment from narcosis have relied on measures of explicit memory. There is a clear distinction made in the literature [e.g. 1] between explicit memory and other types of memory such as implicit and procedural memory. If we are to carry forward the argument that the cognitive processes underpinning memory impairment from narcosis are the same as, or similar to, some drugs it is worth noting that alcohol [44,45,2] and cannabis [46] have both been reported to impair measures of explicit memory while leaving implicit memory intact. If the dissociation between explicit and implicit memory is the same for narcosis this could be important as procedural memory for physical skills constitute a considerable portion of skills learned for diving underwater or operating in other pressurised environments. Arguably implicit memory may be even more important than explicit memory when divers are presented with a dangerous scenario underwater. Thus, further studies considering the effects of narcosis on implicit memory would be welcome.

Impairment from narcosis is a serious safety concern for scientific and commercial undersea divers [47], military divers [9], breath hold (free) divers [48,49], recreational divers [50], technical divers [51], and other workers in pressurised environments [52]. For such populations the observation that it is memory for information that is learned under narcosis that is impaired and not beforehand is both encouraging and provides a point of caution. It is encouraging that crucial information presented at low pressures may be resistant to the effects of narcosis. Thus, information acquired before operating at high pressures (4.4–5.0 atm/34–40 msw) is no more likely to be lost than that learned at shallower depths, despite the presence of narcosis. The point of caution is that important information that becomes available while at high pressures might not be encoded properly and thus not be recalled when needed. This might include important information from instruments (air supply; decompression stops) or navigational cues in low visibility, all of which could influence the likelihood of an accident. Alternatively, divers engaged in scientific or military activities may fail to recall relevant task-related information. One example [9] are military mine countermeasures divers who are required to locate and memorise the fine details of mines and report back accurately to surface support.

## 5. Conclusions

It was concluded that inert gas narcosis disrupts the encoding of information into LTM, while retrieval appears to be unaffected. Furthermore, the pattern of results observed are similar to those found by some memory impairing drugs, suggesting a shared impact on cognition. The findings are also of key practical importance to individuals working in pressurised environments because there may be a selective loss of important information relevant to safety and work performance. Information made available at high pressures may be easily lost, while information learned before arriving at high pressure is resistant to the memory impairing effects of narcosis.

## Conflicts of Interest

We have no conflicts of interest.

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