

Effect of nitrogen narcosis on free recall and recognition memory in open water.

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Hobbs M, Kneller W. Effect of nitrogen narcosis on free recall and recognition memory in open water. *Undersea Hyperb Med* 2009; 36(2):73-81. *Rationale:* Previous research has demonstrated that nitrogen narcosis causes decrements in memory performance but the precise aspect of memory impaired is not clear in the literature. *Objective:* The present research investigated the effect of narcosis on free recall and recognition memory by applying signal detection theory (SDT) to the analysis of the recognition data. *Methods:* Using a repeated measures design, the free recall and recognition memory of 20 divers was tested in four learning-recall conditions: shallow-shallow (SS), deep-deep (DD), shallow-deep (SD) and deep-shallow (DS). The data was collected in the ocean off Dahab, Egypt with shallow water representing a depth of 0-10m (33ft) and deep water 37-40m (121-131ft). The presence of narcosis was independently indexed with subjective ratings. *Results:* In comparison to the SS condition there was a clear impairment of free recall in the DD and DS conditions, but not the SD condition. Recognition memory remained unaffected by narcosis. *Conclusions:* It was concluded narcosis-induced memory decrements cannot be explained as simply an impairment of input into long term memory or of self-guided search and it is suggested instead that narcosis acts to reduce the level of processing/encoding of information.

INTRODUCTION

Nitrogen narcosis refers to the set of cognitive deficits, performance decrements, and alterations in mood and behaviour that result when exposed to increased partial pressures of nitrogen (1). It is most typically experienced by undersea divers at depths greater than 30m, where it impairs underwater work performance and is a significant contributing factor in diving related accidents (2). It has long been recognised that one of the symptoms of narcosis is memory loss (3) but the exact nature of this impairment has not always been well addressed in the literature.

Several studies have investigated narcosis induced memory impairment using hyperbaric chambers. Fowler et al (4, 5) provided evidence that narcosis affects long term memory (LTM) rather than short term or working memory, where LTM denotes memory

that persists beyond the approximate 20s span of short term/working memory. Specifically, they showed that the delayed free recall of word lists is impaired when learned and tested under narcosis. It has been suggested that this indicates narcosis prevents input of information into long term memory (LTM). However, Fowler et al (6) reported that providing word cues in a test of recognition memory corrected this deficit in free recall, suggesting information is stored in LTM and it is self-guided search which is impaired. That is, the process enacted by an individual to retrieve information in the absence of external memory cues. This is supported by Philp et al (7) who reported that free recall was impaired while recognition memory was not affected at a depth of 36m (118ft). Sparrow et al (8) also failed to observe a reduction in recognition memory. The limitation of these studies is that they only included conditions where material was both learned and recalled either under

pressure or outside of the hyperbaric chamber. They did not include conditions that measured recall of material learned at depth to be tested on the surface and vice versa. Thus, it is not possible to determine whether the differential impact of narcosis on free recall and recognition memory reflects an actual impairment of LTM or was an artefact of the measures used (i.e. state-dependent effects; differences in the sensitivity of the free recall measures and recognition measures). The addition of these conditions would allow a much clearer picture to emerge as they allow the impact of narcosis to be measured separately on LTM input and self-guided search.

The one study, by Tetzlaff et al (9), that did include these conditions reported that free recall of material learned at a depth of 50m (164ft) was impaired when tested both at depth and when shallow [0.5m (1.6ft)]. Interestingly, when material was learned at 0.5m and recalled at depth there was no decrement in free recall. This would appear to contradict earlier findings as it suggests the free recall deficit occurs because narcosis affects the input of material to LTM rather than self-guided search. But the matter is further confused as recognition memory remained unaffected throughout by narcosis, suggesting material was actually learned at depth. However, the results of this study should be treated with caution as there was a trend towards an impairment of recognition memory which, although not significant, may have reflected the small sample size (n=12) in each condition.

Additionally, it is possible that any effect of narcosis on recognition memory is more subtle and may not be detected by traditional methods of analysing recognition data, such as proportion of words correctly identified. A method that has gained considerable ground in memory research is that of signal detection theory (10, 11). In a typical recognition test participants are asked to identify 'old' words

they have previously been presented, from 'novel' words. Signal detection theory (SDT) proposes that an individual's response is a function of the sensed intensity of the stimulus (in this case the familiarity of the old words) and the decision criteria they adopt (the likelihood an individual will favour one particular response). For example, if an individual adopted a liberal criterion they would be more likely to respond "yes, it is an old word", whereas if they adopted a conservative criterion they would be more likely to say "no". Thus, it is possible that individuals who adopt different decision criteria could differ on their proportion correct scores when in fact their ability to discriminate between old and new words is the same. An SDT analysis yields two values: decision criterion (C), a measure of the decision criterion adopted; d' , an index of discrimination performance adjusted for variations in the decision criterion. SDT has the advantage over traditional measures as it is able to provide a more accurate assessment of discrimination ability which minimises the biases produced by decision criteria, as well as providing an additional level of analysis in the form of a measure of their decision criteria.

The only study to have utilised this method in relation to narcosis was that by Sparrow et al (8). They reported that, even with a SDT analysis, performance on a recognition memory task was not affected by narcosis but decision criteria was altered, with participants shifting to a more conservative criterion under narcosis. Unfortunately they did not include a measure of free recall for comparison and it is not possible to assess whether narcosis selectively impaired recall in this case. A depth of 30m (98ft) was also used, considered the threshold for the onset of narcosis, and the researchers suggested that the depth may not have been sufficient for an effect on memory performance to have been detected.

The aim of the current research was to carry out a more comprehensive assessment

of the effect of narcosis on free recall and recognition memory, implementing both the conditions used by Tetzlaff et al (9) and utilising a more sophisticated analysis of the recognition data with SDT. The study was run in open water, rather than in a hyperbaric chamber. While chamber studies provide an excellent controlled environment for studying narcosis, they do not necessarily accurately reflect actual impairment underwater (12, 13, 14). Comparative underwater studies are therefore desirable and the present study was intended as a useful comparison to the existing chamber studies. The study compared the effect of learning environment (shallow water vs. deep water) and recall environment (shallow water vs. deep water) on free recall and recognition memory. It was predicted that if narcosis impairs input into LTM both free recall and recognition memory would be impaired when learning took place in deep water (under narcosis), whether recalled in shallow or deep water. Whereas, if self-guided search is impaired, free recall would be impaired when material was recalled under narcosis but recognition memory would not be impaired.

METHOD

Design

The effect of *learning environment* (shallow vs. deep) and *recall environment* (shallow vs. deep) on free recall and recognition memory was measured. Each participant completed all of the following learning – recall conditions: shallow – shallow (S-S); shallow – deep (S-D); deep – deep (D-D); deep – shallow (D-S). The order participants completed these conditions was counterbalanced. Shallow water represented a depth between 0 and 10m (33ft), deep water between 37 and 40m (121ft and 131ft). Subjective measures of narcosis were also recorded in deep water to provide a measure of narcosis independent of the memory tests.

Participants

Twenty participants (18 males; 2 females) aged 20 to 57 years (Mean = 28.9; SD = 8.16) volunteered for the study. The number of dives they had completed was between 11 and 2000 (Mean = 248.75; SD = 494.32) with between 0.04 and 10 years diving experience (Mean = 3.74; SD = 2.71). All participants were customers of the recreational dive centre Big Blue in Dahab, Egypt. An established screening process was conducted by Big Blue which confirmed that participants were suitably qualified and medically fit to dive to the depths required in the study. The study protocol was approved by the Ethics Committee of the University of Winchester and all participants volunteered after providing informed consent in line with the University's regulations.

Measures

Free recall (FR) and recognition memory (RM) was assessed for four word lists. The use of each word list was counterbalanced across conditions, meaning each word list appeared an equal number of times in each condition. Each word list consisted of 30 words, printed on three laminated cards of 10 words each. All conditions consisted of a presentation phase followed by a FR and RM test. In the presentation phase each card was presented for 20s. Between four and five and a half minutes after presentation of all 30 words participants completed the FR test. They were allowed 90s to write down as many words as they could remember from the 30 just presented. This was immediately followed by the RM test. In the RM test participants were presented with 20 words, 10 old words from the presentation phase, and 10 novel words. Participants responded by indicating whether each word had appeared ('yes') or not appeared ('no') in the presentation phase. They were given a maximum of three minutes to complete the RM test. All words were matched for imagery, familiarity and concreteness using

the MRC Psycholinguistic Database: Machine Usable Dictionary (v2.0).

Participants provided subjective ratings for words that have been used in previous research for measuring narcosis (15, 16). Ratings between 0 and 100 (0 = Not at all, 50 = moderately, 100 = extremely) were given as to how participants felt at that moment for 8 adjectives: 'high', 'difficulty concentrating', 'elated', 'confused', 'dizzy', 'light head', 'anxious' and 'intoxicated'. The ratings were obtained once in shallow water in the SS condition and a further three times when in deep water in the DD, SD and DS conditions.

Procedure and Environmental Conditions

Each participant completed the four conditions over the course of three dives. All dives were shore dives conducted out of Dahab in Egypt. Water temperature was between 22 to 24°C, visibility between 15 and 30 metres (49 and 98ft) and there was no noticeable current underwater. The dive sites consisted of a sandy slope with flat plateaus in shallow water and at 37-40m. All participants were breathing normal air.

In the S-S condition participants knelt on the seabed between 0 and 10m. Within two minutes of submersion they were shown one of the word lists, followed by a delay of four minutes, before being handed an underwater slate and completing the FR test and the RM test. In the 4 minute delay participants provided the subjective ratings and completed a digit-letter substitution test, used as data for another study. The protocol for the D-D condition was exactly the same, except it was conducted at a depth of 37-40m. Descent time to 37-40m was between four and six minutes and testing was begun immediately on reaching depth.

In the SD condition participants knelt on the seabed between 0 and 10m and were shown one of the word lists within two

minutes of submersion. Immediately after this presentation phase they swam down the slope to a depth between 37 and 40m and knelt on the bottom, where they completed the FR and RM test in the same manner as the SS condition. The delay between presentation and testing in this condition was between four minutes and four minutes 30s in every case. After the FR and RM test had been completed participants provided their subjective ratings. The protocol for the DS condition was exactly the same, except that the presentation phase took place between 37 and 40m with participants then ascending to a depth between five and 10m for the FR and RM test. A depth of between five and 10m was necessary for this condition so that testing could be incorporated into the safety stops required as a precaution against decompression sickness. The subjective ratings in this condition were also obtained in deep water immediately before the presentation phase. The delay between presentation and testing in this condition was between four and four minutes 30s, except for two participants where the delay was five minutes 30s.

Data analysis

One set of recognition data for the SS condition and one for the DD condition was lost due a complication on one of the dives. For the recognition data the SDT analysis required counting the number of hits ("yes" response for old word) and false alarms ("yes" response for novel words) and then calculating the hit rate (HR – hits/total number of old words) and false alarm rate (FAR – false alarms/total number of new words). HRs of '1' and FARs of '0' were corrected in order to calculate d' . HRs of '1' were corrected using the formula $1 - 1/(2N)$, where N is the maximum number of hits. FARs of '0' were corrected using $1/(2N)$, where N is the maximum number of false alarms. From the HR and FAR d' and C were calculated (10, 11). The FR and RM data was compared by

analysis of variance. Significant main effects were further analysed using follow-up t-tests. An alpha value of 0.05 was used as the criterion of significance.

RESULTS

The results of the subjective ratings are shown in Table 1 (see page 78 for Tables 1-4). With the exception of the rating for 'anxious', all the ratings in the DD, SD and DS conditions (when in deep water) were considerably higher than in the shallow water (in the SS condition). This suggests that, regardless of the results on the memory tests, participants were experiencing narcosis in deep water. The ratings were not towards the higher end of each scale, which might be expected given that extreme narcosis was unlikely to occur given the depth of testing. Furthermore, the uniformity of the subjective ratings suggests the degree of narcosis was comparable across each deep water condition.

Table 2 shows the results of the FR test. The mean number of words recalled in each condition and the percentage of words correctly recalled are displayed. The free recall of words was higher in the control SS condition compared to all the other conditions. The decrement was largest in the DD condition but was also lower in the DS and SD conditions. A repeated measures ANOVA revealed a significant effect of learning-recall condition [$F(2.57, 54) = 8.197, p < .01, \eta_p^2 = .31$]. The results of the follow-up t-tests (shown in Table 3) confirmed that free recall was significantly higher in the SS compared to DD and DS conditions but not the SD condition. Free recall in the DD condition was significantly lower than the SD but not the DS condition. The DS and SD conditions were not significantly different from each other.

Table 4 shows the mean number of words correctly recognised in the RM test. No clear differences in performance between

the four conditions were apparent. A repeated measures ANOVA confirmed no significant effect of learning-recall environment on these proportion correct responses [$F(3, 51) = 0.88, p > .05, \eta_p^2 = .05$]. For the SDT analysis, a repeated measures ANOVA revealed no significant effect of learning-recall environment on d' [$F(3, 51) = 0.83, p > .05, \eta_p^2 = .05$] or for C [$F(3, 51) = 1.49, p > .05, \eta_p^2 = 0.12$] on the recognition test, indicating that recognition memory was not affected by narcosis.

DISCUSSION

Narcosis significantly impaired free recall when material was learned at depth and recalled in deep or shallow water, compared to material both learned and recalled, free of narcosis, in shallow water. Free recall was not impaired when material was learned in shallow water and recalled at depth. In contrast recognition memory was unaffected by narcosis as measured by both proportion of words correctly identified and a SDT analysis. The increase in all of the subjective measures, except for anxiety, from shallow to deep water indicated the divers noticeably experienced symptoms of narcosis and the uniformity of these reports suggest that the degree of narcosis was comparable across the SD, DS and DD conditions.

These results support the findings of earlier research showing that free recall is impaired by narcosis (4, 7) and those studies demonstrating a selective impact of narcosis on free recall and not recognition memory (6, 7). The pattern of results was also the same as those reported by Tetzlaff et al (9). The advantage of the current study was that this was found with a SDT analysis and at a depth beyond the threshold for narcosis, with narcosis independently indexed by subjective report. Taken in isolation, the fact that free recall was

Table 1. Mean (+SD) subjective ratings for each learning-recall condition

	Condition			
	SS	DD	SD	DS
High	2.1 (7.1)	27.7 (29.5)	25.0 (24.7)	24.2 (24.5)
Confused	0.6 (14.9)	13.1 (14.9)	11.6 (14.9)	9.2 (14.0)
Elated	3.1 (8.2)	27.6 (27.7)	28.8 (29.3)	29.1 (29.2)
Dizzy	0.5 (2.3)	7.1 (14.3)	12.9 (24.1)	13.7 (23.8)
Light head	0.0 (0.0)	22.9 (25.6)	29.1 (23.5)	26.2 (23.6)
Intoxicated	1.1 (4.6)	18.7 (15.4)	25 (26.2)	26.3 (25.7)
Anxious	14.5 (20.0)	12.6 (17.0)	9.8 (15.6)	11.84 (17.9)
Diff. conc.	2.4 (9.2)	21.6 (22.4)	28.3 (26.6)	26.7 (27.4)

Note. Diff. conc. = ‘difficulty concentrating’

Table 2. Mean (+SD) number of words recalled for each condition

	N	Mean	SD	% recalled
Shallow – Shallow	19	5.26	2.35	17.5
Deep – Deep	20	2.65	2.37	8.8
Shallow – Deep	20	4.40	1.85	14.7
Deep – Shallow	20	3.55	2.91	11.8

Table 3. Results of paired t-tests for free recall

Condition	df	t	dz	sig.
SS vs DD	18	4.3	0.79	<.01*
SS vs SD	18	1.76	0.34	.09
SS vs DS	18	2.61	0.51	<.02*
DD vs SD	19	3.35	0.75	<.01*
DD vs DS	19	1.65	0.37	.12
SD vs DS	19	1.39	0.31	.18

Note: * = significant at .05 level; dz = effect size.

Table 4. Mean (+SD) number of words correctly recognised for each condition

Condition	N	Mean	SD
Shallow-Shallow	19	11.95	2.32
Deep-Deep	19	12.12	2.54
Shallow-Deep	20	12.35	2.23
Deep-Shallow	20	11.15	1.90

impaired when material was learned at depth but not when material was learned in shallow water and recalled at depth, suggests narcosis impaired the input of material into LTM, rather than self-guided search. But, as with previous research (8, 9), the fact that recognition memory was unaffected shows that the material was learned in some way. This pattern of results demonstrates that viewing the effect of narcosis on memory as simply an impairment of input into LTM or self-guided search is not sufficient and a more sophisticated explanation is required. Several explanations for the current findings can be presented.

Firstly, it has been reported that anxious divers display greater impairment under narcosis compared to non-anxious divers on measures such as manual dexterity (12, 13, 14, 17). It is possible that this effect could translate to memory measures and explain the differences in free recall. This explanation is unlikely as analysis of the subjective anxiety ratings revealed no significant difference between the four conditions [$F(3, 48) = 1.20, P > .05$]. In addition, previous research has not found memory performance under narcosis to be affected by anxiety as measured by physiological stress (9).

Secondly, there were three methodological concerns. In the SD and DS conditions the divers spent the time between the presentation phase and the memory tests descending or ascending to the required depth. But in the SS and DD conditions the divers completed a digit-letter substitution test for another study. It was assumed that the act of swimming in the DS and SD conditions would act as a suitable distracter task to interfere with rehearsal strategies in the same manner as the digit-letter substitution test. It cannot be verified if this was the case and the divers could have implemented more effective rehearsal strategies whilst swimming in the SD and DS conditions. While this partially explains the lack of

impairment in free recall for the SD condition, it would be expected that there would then be a comparative effect on the DS condition, but this was not the case. The second concern was that because the FR test always came before the RM test the words remembered in the FR test could have 'primed' the participants for the recognition stage. Participants that recalled words presented in the RM test almost always responded correctly in the RM test and this may have obscured any effect of narcosis on the recognition memory. To test this concern, these responses were deleted and the data reanalysed. Although this resulted in reduced hit rates there was no change in the results, suggesting that the order of the FR and RM test did not unduly affect the recognition responses. The third concern was that the measures were taken after differing periods of submersion and exposure to narcosis. For example, the FR test in the DD condition was completed after at least four minutes under the effects of narcosis, whereas it was completed immediately upon reaching depth in the SD condition. Other timing discrepancies were present across conditions which were an unavoidable result of conducting a field study. This may be pertinent in that the effects of narcosis have been reported to be most severe at initial exposure followed by adaptation on some measures if exposure continues (18). While this concern should be acknowledged it is unlikely to have seriously influenced the results as exposures of periods up to one hour appear not to result in adaptation (19), with the divers in this study exposed to narcosis for only approximately 10 minutes.

The third and most likely explanation is that the pattern of impairment reported occurs because encoding under narcosis produces a weaker memory trace than normal. It has been suggested narcosis disrupts processing when learned material is encoded (20), causing fewer cognitive resources to be available to encode than normal. The result is material is learned

but the quality of encoding and processing is reduced, producing a weaker memory trace. Supporting this is previous memory research showing that recognition is generally easier than free recall (21, 22) as, according to Tulving (23), the overlap between the original memory and the information provided in a recognition test is stronger than in a free recall test. As Tetzlaff et al (9) remarked ‘if information is not encoded in a sophisticated manner the flexibility of response generation strategies’ that are required in free recall ‘can be reduced’. In comparison in a recognition task the possible responses are provided by the experimenter, requiring a less ‘sophisticated’ level of processing. This explanation would predict that 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. While evidence in the narcosis literature is sparse for this idea it would explain why impairment was found when material was learned at depth (DD; DS conditions) and not when material was learned in shallow water (SD condition), despite the presence of narcosis at recall in the SD condition. It would also explain why there was no impairment of recognition memory as it allows for some learning to take place. It is therefore suggested that further research investigates the hypothesis that narcosis effects the strength of the memory trace at the encoding stage by examining whether deeper processing at encoding can reduce the effects of narcosis (24).

It should be noted that the data does not support the findings reported by Sparrow et al (8). They reported that recognition memory was not affected by narcosis but they did report that their participant’s decision criteria became more conservative under narcosis. They related this to the slowed processing model (18) and suggested that narcosis affects strategic variables, rather than slowing perceptual processes. In the present study, there was no

evidence of an alteration in decision criteria under narcosis. Sparrow et al (8) used a different index of decision criteria (β) but when an analysis of the current data using β instead of C was conducted the results were unaffected.

The repeated measures design in the current study provided larger sample sizes per condition than most previous studies in this area but the effect sizes generated from the analyses showed considerable variation and meant that observed power values sometimes fell short of acceptable levels (<0.80) when the effect sizes were small. This should be considered when viewing the results of this study as some meaningful effects may have been missed. Future researchers in this area are urged to increase their sample sizes and thus confidence in observed effects.

Finally, the data above provides a comparison of memory decrements between hyperbaric chambers and the actual the underwater environment. The divers remembered 17.5% when words were learned and recalled in shallow water compared to 8.8% of words when learned and recalled at depth. This is comparable to the size of the decrement reported by Philp et al (14.7% on the surface and 7% at 36m), suggesting that memory decrements in hyperbaric chambers are comparable to those underwater (7).

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