Rapture of the deep: gas narcosis may impair decision-making in scuba divers

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Abstract
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Introduction: While gas narcosis is familiar to most divers conducting deep (> 30 metres) dives, its effects are often considered minuscule or subtle at 30 metres. However, previous studies have shown that narcosis may affect divers at depths usually considered safe from its influence, but little knowledge exists on the effects of gas narcosis on higher cognitive functions such as decision-making in relatively shallow water at 30 metres. Impaired decision-making could be a significant safety issue for a multitasking diver.
Methods: We conducted a study exploring the effects of gas narcosis on decision-making in divers breathing compressed air underwater. The divers ($n = 22$) were evenly divided into 5-metre and 30-metre groups. In the water, we used underwater tablets equipped with the Iowa Gambling Task (IGT), a well-known psychological task used to evaluate impairment in decision-making.
Results: The divers at 30 metres achieved a lower score (mean 1,584.5, standard deviation 436.7) in the IGT than the divers at 5 metres (mean 2,062.5, standard deviation 584.1). Age, body mass index, gender, or the number of previous dives did not affect performance in the IGT.
Conclusions: Our results suggest that gas narcosis may affect decision-making in scuba divers at 30 metres depth. This supports previous studies showing that gas narcosis is present at relatively shallow depths and shows that it may affect higher cognitive functions.

Introduction

Diving requires constant evaluation of the changing underwater environment. The level of alertness and consciousness changes as the diver moves through the vertical water column. A scuba diver is dependent on the breathing gas they carry, and the breathing gas affects the nervous system and cognitive functions of the diver. While gas narcosis is familiar to many divers conducting 'deep' dives (> 30 metres [m]), its mechanisms and effects at shallower recreational depths (often considered as maximum 30 m) are poorly understood.[1]

Both in the hyperbaric literature[2–4] and in the dive community, dives to 30 m or shallower are often considered relatively safe from the effects of narcosis. However, research has shown that immersion at depths as shallow as 5 m can cause cognitive impairment in divers (not necessarily due to gas narcosis),[5] and many other chamber,[1] animal,[6] and open water studies[7–9] show various changes in cognition under hyperbaric pressures. Many of these studies have focused on the effect of narcosis on memory, and research suggests that it is not the short-term memory but the long-term memory that is affected by narcosis.[10,11] More recent research has shown that narcosis particularly affects the free-recall memory, but only when the information was learned at depth under narcosis.[9] The retrieval of information, whether under narcosis or at shallow water, was not impaired.[9] These results and further studies suggest that narcosis affects the encoding of information into long-term memory, rather than the information retrieval.[7]

While memory is an integral part of most cognitive functions, successfully conducting a dive requires several cognitive and executive functions such as coping with new situations, self-regulation, and decision-making. Both Divers Alert Network (DAN) annual reports on diving fatalities, injuries, and incidents,[12] and British Sub-Aqua Club (BSAC) diving incident reports from previous years[13] reveal that nitrogen narcosis has been a contributing factor in many accidents and incidents that have occurred at depth (20–60 m). The incidents varied from slight confusion that was resolved by ascending, to lethal entanglement. The most remarkable issue with narcosis is that it impairs the diver's capacity to respond to a potential issue underwater.[4,12,14]

While initial studies show that decision-making can be impaired as shallow as 5 m,[5] it is known that other higher executive functions, namely inhibitory control ability, are impaired at 20 m.[15] Making decisions requires multiple cognitive functions: retrieving information from and encoding information into long- and short-term memory, assessing the information and the options available in the current context while potentially experiencing various emotions, and deciding the best course of action. Because of decompression and gas limitations, decisions underwater must be made quickly. Understanding the effect of narcosis on such higher cognitive functions could greatly improve diver safety and training.

The Iowa Gambling Task (IGT)[16] is a widely used neuropsychological task designed to assess impairments in decision-making.[17] The IGT was originally used to assess decision-making in patients with injury to the ventromedial prefrontal cortex, an area known to be linked to poor decision-making in complex and uncertain situations. The IGT has been specifically designed to predict real-life decision deficits. It has since been used as a clinical diagnostic measure to assess decision-making in individuals with neurological disorders, psychiatric disorders, nonclinical populations, and animal models.[17] It is the most commonly used tool to assess decision-making in people with alcohol use or gambling disorders.[18]

Given the similarities in the symptoms of gas narcosis and alcohol intoxication, and that both alcohol and nitrogen are thought to affect areas in the prefrontal cortex, an area important for decision-making,[16] the IGT could be a suitable tool to study the effect of gas narcosis on decision-making in divers. To address the knowledge gap on the effects of gas narcosis on decision-making, we trialled the use of IGT to study decision-making in scuba divers potentially experiencing narcosis. Specifically, we addressed the following question: does gas narcosis affect the performance in IGT in scuba divers breathing compressed air at 30 m compared to a control group at 5 m? To our knowledge, this is the first time the IGT is used to study decision-making in scuba divers.

Methods

The study protocol was approved by the University of Jyväskylä Ethics Committee and all participants were volunteers and provided written informed consent.

PARTICIPANTS

A total of 25 participants (male n = 18, female n = 7) were recruited through local Finnish dive clubs. The participant had to be a minimum of Professional Association of Diving Instructors (PADI) advanced open water diver or equivalent (i.e., certified to dive to 30 m), capable of diving in a dry suit, answer 'no' to all questions in the PADI medical statement or get a doctor's certificate to prove fitness to dive, be over the age of 18, and their last dive must have been within a year. The least experienced diver had 40 dives, and the most experienced diver had > 2,000 dives (median 180, mean 360, standard deviation [SD] 454). The certification level of participants varied from advanced open water diver to technical diving instructor. The mean body mass index (BMI) was 25.6 (SD = 3.9). The BMI was included because the correlation between body fat and other pressure related issues such as decompression sickness is well-known, so we wanted to see any potential effect, however unlikely, it could have on narcosis.

LOCATION, CONDITIONS, AND MATERIALS

The experiments were carried out over three days in October 2019. The study took place at the Kaatiala quarry in Ostrobothnia, Finland. Kaatiala is a popular dive site among Finnish divers, it has relatively stable and clear conditions, and a gravel bottom which limits silting up. The maximum depth of the open water quarry site is 30 m. On our test dates, the water temperature was approximately 6°C at 5 m and 4°C at 30 m. The horizontal visibility was measured using a secchi disc and a measuring tape, and was between 6 and 7 m both at the control depth of 5 m and at the bottom at 30 m. We used four identical Samsung Galaxy A 8'' tablets in underwater housings (Alltab, Valtamer Ltd, Helsinki), that had the Iowa Gambling Task[16] application (https://www.apkmonk.com/app/com.zsimolabs.iowa) installed. One housing got damaged and flooded on the first dive, so for the rest of the experiment, only three tablets were used. All participants used compressed air as a breathing gas and were on open-circuit scuba with their own, standard dive equipment, including their own dry gloves.

STUDY DESIGN

Each participant filled out a Finnish translation of the Behavioural Inhibition System (BIS) and Behavioural Activation System (BAS) questionnaire[19] before the dive. The BIS/BAS questionnaire is a 20-point self-report questionnaire, designed to assess the motivational systems underlying individual behaviour. Questions measuring the inhibition system assess the motivation to avoid aversive outcomes, while questions measuring the activation system assess the motivation to approach goal-oriented outcomes. The answer scale is a 4-point Likert scale. The participants' BAS scores were then ranked in order from the lowest to the highest, and every other participant was allocated to the 5-metre or 30-metre group respectively. Those in the 5-metre group would take the IGT test at 5 metres, and those in the 30-metre group would take the IGT at 30 metres. The results of the BIS/BAS questionnaire are known to be linked to the results of the IGT,[20] so the group allocation was done to reduce the effect of individual variation in risk-taking tendency. In total 12 participants were allocated to 5 m and 13 to 30 m. Regardless of whether the participant had been allocated to the 5 m or 30 m group, the test dives were done in groups of two to five people, including the researcher. Each participant was given a tablet that had been turned on at the surface and the test had been set ready so that it could be started with two presses of a (touch-screen) button underwater. The task had been explained to the participants in advance as part of the standard pre-dive briefing, but they had not seen the actual task. The groups descended to their target depths following regular dive guidelines and a maximum descent rate of 20 m·min^{-1}. The groups descending to 5 m did a free descent with a wall as a visual reference and the 30 m group used a fixed line as a visual reference.

The IGT test has four buttons representing card decks, labelled A, B, C, and D. The participant is given a USD$2,000 'loan' to start with, and their aim is to make as much money as possible. The participant has a total of 100 cards in four decks and they choose (i.e., press the deck label) one card at a time. With each card, they either lose or win money. They have no prior knowledge of which decks will yield the most money and which decks will lose the most money. The decks A and B are 'high risk' decks, as they always win USD$100 but also incur occasional large losses of up to USD$1,250. Decks C and D are 'low risk' decks resulting in small wins of USD$50 in each trial and occasional small losses of up to USD$250. The decks A and B will result in a net loss of USD$250 over 10 trials on average, while decks C and D will gain USD$250 over 10 trials. The decision-maker receives win and loss information and total current gain or loss after each trial. Completing the 100 trials took approximately 10 minutes, and after that, the participant locked the tablet screen and ascended to the surface together with the group following regular dive guidelines. Divers ascending from 30 m did a 3-minute safety stop at 5 m. Consequently, the average total dive time was as follows: descent (20 m·min^{-1}) + IGT (10 min) + ascent following computers (10 m·min^{-1}) + safety stop for the 30-metre group (3 min). Due to gas constraints, no acclimatization time was included.

The IGT software automatically recorded the participant's random ID, number of trials, the chosen deck (A, B, C, or D), reward, penalty, gain, total amount of money, response time, touch speed, and time (with one-second accuracy). All these data were saved on the tablet memory and retrieved after all the experiments were completed.

DATA ANALYSIS

To test the effect of depth (categorical variable with two levels: 5 m and 30 m), and any potential confounding influence of dive experience (number of dives), BMI, age, and gender (categorical variable with two levels: male and female) on the response variable of IGT score (i.e., the total amount of money the diver 'won' in the IGT), a generalised linear model (GLM) from the R package 'MASS'[21] was used. A negative binomial distribution was used to account for overdispersion. The model assumptions were checked by visually inspecting model diagnostics plots. A backwards stepwise model selection and Akaike Information Criterion (AICc and QAIC) from the R package 'MuMIn'[22] were used to select the model of best fit. A χ^2-test for the difference in null deviance and residual deviance was done to check for the goodness of fit of the model. All analyses were conducted using R version R-4.0.3.[23]

Results

As a result of complete tablet and housing malfunction underwater, the results of three participants had to be excluded from the analyses. A total of 22 participants were therefore included in the final analyses. Of these 22 participants, three had their tablet malfunction before they reached the end of the task. In order to keep the sample size as high as possible, we did not exclude those three. Out of one hundred IGT card trials, these three had completed 99, 81, and 79 trials respectively. Their test results were treated as 99, 81, and 79% of the full score and their final scores were corrected respectively. The IGT score was therefore achieved from a total of 22 participants, 11 of them at 5 m and 11 at 30 m. The score used was the total amount of money achieved at the end of the task. The IGT software also recorded the response time, touch speed, and total time. While these could be interesting variables to investigate, we omitted them from the analyses due to the practical challenges faced by participants when handling the underwater housing with dry gloves. The participants wore their own personal gloves

Table 1

Summary of the number (n) of participants, gender distribution, number of dives, age, body mass index (BMI) and Iowa Gambling Task (IGT) scores, by test depth (5 m or 30 m) and all divers combined; F – female; M – male; SD – standard deviation

Depth	*n*	M/F	Previous dives Mean (SD)	Age (years) Mean (SD)	BMI Mean (SD)	IGT score Mean (SD)
Total	22	15/7	360 (454)	35.2 (10.3)	25.6 (3.9)	1823.5 (559.6)
5 m	11	8/3	326 (570)	33.6 (11.1)	25.0 (3.5)	2062.5 (584.1)
30 m	11	7/4	393 (324)	36.8 (9.6)	26.3 (4.4)	1584.5 (436.7)

Figure 1

The lack of relationship between the IGT score and the number of dives; due to the few extreme values in the number of dives, this parameter is shown on a logarithmic scale

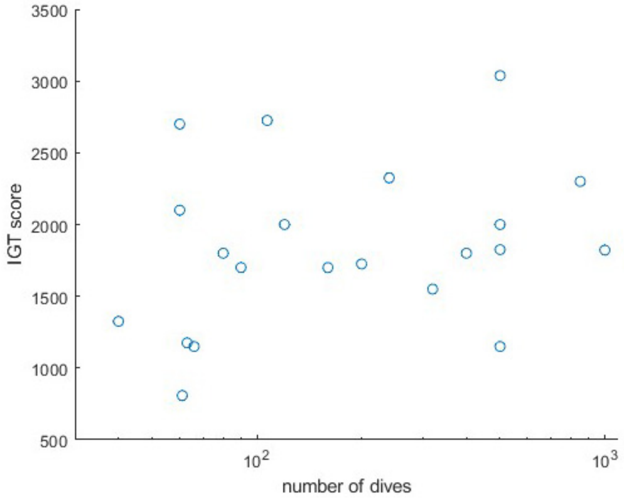
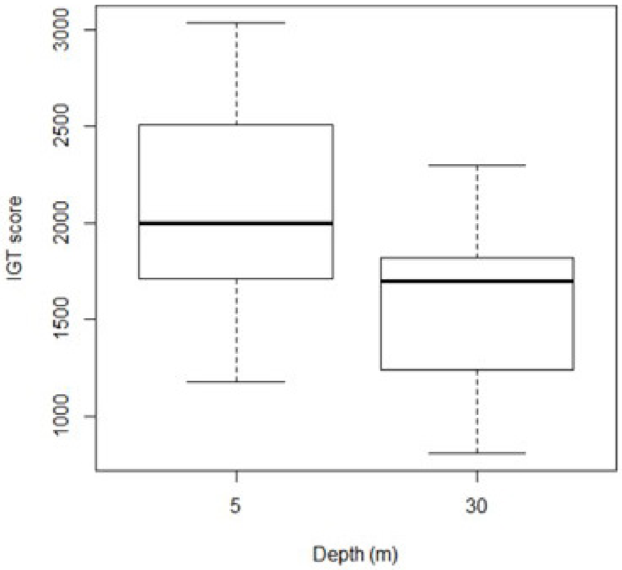


Figure 2

Boxplot of the effects of depth on the IGT score; the horizontal line inside the box shows the median, the ends of the box show the upper and lower quartiles, and the whiskers show the highest and lowest scores



and it was obvious that the underwater housing responded better to some dry gloves than others, and therefore any time-related variable would not be reliable. The break down summary of participant gender, number of dives, age, BMI and the IGT score by depth is detailed in Table 1.

The best fitting model was $Y_i \sim \beta_0 + \beta_1 D_i$ where Y_i = the IGT score, β_0 = the intercept, and D_i = depth as a categorical variable with two levels (either 5 or 30 m). The effect of the number of dives (Figure 1), BMI, age, and gender were not statistically significant, but the model showed a significant relationship between depth and the IGT result so that participants at 30 m has lower scores than participants at 5 m (Figure 2, Table 1) (GLM, z = -2.243, P = .025, DF = 20).

The χ^2-test for the difference between the null deviance and residual deviance was P = 0.025, indicating that the model is an adequate fit for the data.

Discussion

Our results show that divers at 30 m achieved lower scores in the IGT than divers at 5 m. This means that at 30 m the divers chose 'riskier' decks, i.e., those that yield high rewards but also high losses and always result in a loss in the long term. In contrast, those at 5 m forewent the immediate rewards and chose decks that yield low rewards but also low losses, and in the long term earn the decision-maker more money. The difference in the scores at 30 m and 5 m suggests that gas narcosis could affect the decision-making process in divers breathing compressed air at 30 m of fresh water, compared to divers at 5 m. While our study did not compare the difference in the performance between the surface and underwater, our results are in line with other studies showing impaired cognitive functions at modest depths: such as a study that showed impaired control of the inhibitory system in divers when measured with the Stroop test at 20 metres,[15] and a study that showed that performance-related cognitive skills, sustained attention in particular, are affected at as shallow as 5 m.[5] We also assessed the effect of the number of previous dives, BMI, age, and gender, and none of these had a significant effect on the IGT result.

Previous non-diving related studies have shown that participants with impediment to the prefrontal cortex, an area important in decision-making, gain lower scores in the IGT compared to those with no damage to the prefrontal cortex.[17] Gas narcosis is the result of exposing neurological tissue to high partial pressures of gases, but the exact mechanisms behind gas narcosis are still unknown. Those mechanisms are likely similar to those of other anaesthetics and take place at the brain synapses.[4] In the current study, it is likely that the impaired decision-making at 30 m could be a result of abnormal activity in the prefrontal cortex, caused by the elevated partial pressure of nitrogen.

Memory is an integral part of decision-making, and previous studies have shown that impairments in working memory can influence the performance in IGT and therefore affect decision-making.[24] However, narcosis affects mainly long-term memory, and not short-term memory.[7,10,11] Given that working memory is part of short-term memory,[25] this could indicate that the impaired decision-making at depth is not simply a relic of impaired memory at depth, but that narcosis also affects higher cognitive functions.

The experience of the diver, measured in the number of dives, did not influence the performance in IGT. While experience usually improves diving skills, and therefore may make it easier to respond to an incident, research shows little correlation between dive experience and adaptation to narcosis,[26] in line with our results.

It is also important to recognise that narcosis has a subjective and objective component and that the relationship between these is not clear. Anecdotal tales of gaining tolerance to narcosis can probably be attributed to the subjective rather than the objective component of narcosis. Similarly, narcosis may affect the metacognition of the diver, and the diver's confidence to perform well may depend on the difficulty of the task at hand. In contrast, it has been shown that although narcosis causes impairment in cognitive functions at 33–42 m, the divers' awareness of it is good, and therefore they might be able to compensate for it.[27] Given that our results show impairment in decision-making, the question of whether they would decide to compensate for the impaired cognitive functions or have the skills to do so while under narcosis, requires further research. However, experience may affect how well the diver is aware of their cognitive degradation underwater, and experienced divers might be more aware of their cognitive functions in the water than inexperienced divers.[5]

The diver's awareness of self and the surroundings is an important part of diver training at all levels. In the dive community, it is often thought and taught that factors such as dehydration, tiredness, temperature, task loading, current, and visibility may affect how strongly the diver experiences narcosis. It could be argued, for instance, that the 2ºC difference at 5 and 30 metres in our study could affect the results. However, there is no scientific consensus on this. Recent research suggests that it is likely that only the breathing gas and the absolute pressure contribute to narcosis.[28] In practice, however, it could be reasonable to assume that the level of (at least) subjective narcosis is affected by various factors, as narcosis, coldness, fatigue, and other factors can accumulate. In the current study, the divers were not faced with any additional tasks such as navigation, highlighting the role of absolute pressure in decision making.

Our results showed no relationship between IGT performance and gender or age. However, outside of the diving context, both are known to affect the performance in IGT. It is thought that the differences in decision-making strategies between men and women have neurobiological and hormonal basis, and the differences are mainly strategic: women decide based on detailed information, while men decide on global information.[29] It could be that narcosis affects decision-making more than just gender does, however, our sample size is too small and unbalanced in terms of genders, and therefore no conclusions on the effect of gender on the IGT results under narcosis can be drawn. Similarly, age is known to affect the performance in IGT, especially during early childhood, adolescent years and after 60 years of age,[30] but the age variation within the participants in the current study was too small to draw any conclusions.

One of the strengths of the present study is that its participants were from the general recreational diving community and were heterogenous in terms of dive experience. A lot of dive-related research is conducted on navy divers. While the advantage of this is that they often have detailed medical evaluations and a detailed record of their dive history, which helps in the standardisation of the experiment, the study population itself tends to be rather homogeneous and mainly consists of healthy and physically fit men of around the same age. The general diving population, however, consists of people of different ages, experience levels and fitness levels. The extrapolation of research results from a homogenous group to a very heterogenous group obviously posits various issues.

LIMITATIONS

The present study has limitations that should be considered. Due to the small sample size, care should be taken when interpreting the results. A potential issue in the present study is that it was not double-blinded. Both the researcher and the participants knew that the effects of nitrogen narcosis were being studied. There are, however, ethical and practical issues in conducting this kind of study without telling the participants what is being studied. Also, the observed effect could have been explained by an unknown difference in the groups.

Due to the learning effect in the IGT, a within-subject design was not possible. Future studies focusing on the effects of decision-making in divers and using the IGT could, however, probably benefit from two additional groups of test subjects: a group of divers and a group of non-divers who take the IGT on land or just below the surface. Given that cognitive functions are known to impair at as shallow as 5 m,[5] repeating the IGT on land (or just below the surface) could exclude any potential effects on cognitive functions from immersion in shallow water. Including a non-diving group could help in evaluating whether the potential long-term effects of exposure to high partial pressures of gases may extend their influence on performance in the IGT. Additionally, a questionnaire about the subjective feelings of narcosis could also add value to any further studies. Currently, no studies exist on the effect of different gas mixes on the higher cognitive functions. Repeating the current study with different gas mixes at different depths could reveal important information on the effects of pressure and breathing gases on the cognitive functions of a diver.

Conclusions

In summary, our results demonstrated that divers at 30 m performed worse in the IGT than divers at 5 m. It is likely that this was caused by gas narcosis, but given the relatively small sample size, the results should be interpreted with caution. The number of dives, age, BMI, and gender did not appear to influence the performance in the IGT.

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