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Memory and attention while SCUBA diving at shallow and deep depths: An open water study

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Abstract

SCUBA diving requires a high level of cognitive functioning, however, many divers anecdotally report poor memory and attentional skills while underwater. Few studies have documented cognitive deficits resulting from an open-water dive. Here, 23 divers completed both shallow (8 m) and deep (28 m) dives over two days in the open-water. The order of the dives was counterbalanced across participants. While at depth, they completed the State-Trait Anxiety Inventory to assess anxiety levels, learned and were tested on a list of 36 words, and completed the trail making task (TMT) to assess executive functioning. They also gave saliva samples to measure cortisol levels before and after each dive and completed the Profile of Mood States survey after each dive on the boat. Divers remembered fewer words, took longer to complete the TMT, and exhibited higher cortisol levels following a deep dive; they reported no changes in anxiety or mood states. The results contribute to our understanding of how cognition is affected by pressurized environments and has implications for divers, as well as others who engage in high-altitude sports.

Keywords

executive functioning, cortisol, stress, anxiety, nitrogen narcosis

Cover Page Footnote

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Memory and attention while SCUBA diving at shallow and deep depths: An open water study

Current standards require SCUBA divers to complete certification programs that teach the many safety protocols involved in diving. Divers must be in good physical health and maintain a certain level of fitness. Importantly, divers must possess strong cognitive functioning to ensure that that they can remember their training and follow protocols for safe diving. Many divers will not dive if they feel as though their cognitive function is compromised before the dive. However, many divers report cognitive changes while they are diving such as not being able to focus or remember things as well as they do on the surface. This is especially true for deeper dives, those beyond 20 m.

There are many reasons to believe that deeper dives may lead to bigger changes in cognitive dysfunction. First, temperature decreases with depth and exposure to cold temperatures results in poorer recall memory (Baddeley, Curaro, Egstrom, Weltman, & Willis, 1974), increased reaction time (Stang & Weiner, 1970), and poorer mental manipulation (Giesbrecht, Arnett, Vela, & Bristow, 1993). Second, light penetration drops with depth. With reduced visibility, divers rely more on their past knowledge than on what is right in front of them (Emmerson & Ross, 1987; Stanley & Scott, 1995). They must remember the location of objects such as the direction of their guide ropes and instructions for basic dive tasks such as checking one's air supply often and reading a compass. They must also remain more vigilant under reduced visibility conditions, always knowing where their dive buddy is located and being cognizant of not swimming into or touching marine life. Third, inert gas narcosis occurs when breathing high partial pressures of nitrogen which leads to a reversible alteration in consciousness. While a diver's cognition may be affected by nitrogen narcosis at depths as shallow as 10 m, it is not usually noticeable until deeper depths are reached (Hamilton & Kizer, 1985; Petri, 2003). Finally, although more experienced divers get better at some of these tasks as routine behaviors become more automatic, and thus require less attention, every diver must remain vigilant and be ready for unexpected scenarios. Remaining vigilant is stressful and since stress level impacts memory (Lupien, Maheu, Tu, Fiocco, & Schramek, 2007; Tsigos & Chrousos, 2003), divers who are more stressed while diving and who dive at deeper depths where the risk is greater may experience greater levels of cognitive dysfunction.

The role that stress and anxiety may have on cognitive functioning are especially important to consider since these can impact memory and attention. Palozzi et al. (2010) took blood samples after divers reached depths between 10 and 50 meters in 3 separate dives. In all divers and after each dive, there were elevated levels of cortisol, prolactin, and adrenocorticotropic hormone (ACTH), indicating elevated levels of physical and mental activation and vigilance. Pourhashemi et al. (2016) examined the effect that one 20-minute, 10-meter dive had on divers' mental and cognitive states. They found that cortisol and mental fatigue levels increased, and reaction time and sustained attention decreased after the dive suggesting that participants found diving to be stressful and cognitively demanding, and that these effects lasted beyond the duration of the dive. Further, it is possible that these effects might be worsened at deeper depths.

Germonpré et al. (2017) assessed diver cognitive abilities during a .4MPa simulated dive (40 m) in a hyperbaric chamber before, during, and after a simulated dive. The divers were given a battery of cognitive tasks and noted their fatigue levels over time while breathing either air or EANx40 (Enriched Air Nitrox 40%). The researchers found that while simple reaction time was not affected by time, depth, or gas, divers' processing time, memory, and attention worsened with depth and over time; these effects were more profound for those breathing air.

Here we evaluate the effect that diving depth has on physiological, psychological, and cognitive functioning in the same diver in an open water environment. Previous studies have examined one or more of these measures, but none have recorded the same data from the same participants in an open water environment. We collected the data at both shallow (8 m) and deep (28 m) depths, including cortisol levels before and after each dive, self-report measures of anxiety during each dive and mood after each dive, and administered paper and pencil cognitive tests that measured memory and attentional control during each dive (Figure 1). We hypothesized that stress and anxiety would be elevated, and that memory and attention would be worse during the deeper dive.

Figure 1. Pictures taken during data collection at deep (left) and shallow (below) dive sites. *Photo credit:* Kirk Kilfoyle.

Methods

Participants

Participants were required to complete two dives on two separate days, separated by at least 24 hours, and be at least advanced level SCUBA certified. An initial sample of 29 participant divers were recruited for this study; 6 participants were excluded from the data analysis for the following reasons: 3 participants only completed 1 dive, 1 participant went diving the morning before one of the research dives, and data from 2 participants was unreadable due to researcher diver error. Thus, our final sample size was 23 (12 males); see Table 1 for participant information. All divers except for one used their own dive equipment. All study procedures were approved by the Nova Southeastern University Institutional Review Board. The study materials and procedures were preregistered with the Open Science Framework before any data was collected (https://osf.io/4adk8/).

Table 1. Demographic data.

Description	Statistic
N	23
Average (stdev) age	32.3 (11.6)
Average (stdev) BMI	26.5 (4.9)
Median number of lifetime dives	105
Mean (stdev) of lifetime dives	509 (1085)
Range of lifetime dives	12 - 5000
Median number of days since last dive	7
Median number of days since last deep dive	21
Mean (stdev) number of hours slept night before dive 1	7.9 (1.3)
Mean (stdev) number of hours slept night before dive 2	7.6 (1.1)
Number of participants who took seas sickness medicine before both dives	3
before deep dive	1
before shallow dive	1

Materials

Cortisol sampling: Saliva samples were taken from each participant before and after each dive. Saliva samples were run in duplicate and quantified via a human cortisol enzyme immunoassay kit per the manufacturer's instructions (Salimetrics LLC, USA)) which has a 0.91 correlation with serum and a sensitivity < 0.007 ug/dL. The samples were then immediately read in a BioTek ELx800 plate reader (BioTek Instruments, Inc., USA) at 450 nm with a correction at 630 nm. The variation of sample readings was within the expected limits. Final concentrations for the biomarkers were generated by interpolation from the standard curve in µg/dL. All participants were asked not to eat or drink anything besides water for at least an hour before the samples were taken.

State-Trait Anxiety Inventory (STAI): The STAI is 20-item questionnaire that measures anxiety in adults (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983) and displays high validity (Smeets, Merckelback, & Griez 1996).

Short-term Memory Task: This task closely matched the criteria used by Godden & Baddeley (1975, 1980) in their underwater short-term memory studies. In the learning phase, participants were given 2 minutes to learn a list of 36 unrelated, 2-syllable words from the Toronto Word Pool (Friendly, Franklin, Hoffman, & Rubin, 1982). We created 6 word lists in total, one for each day of data collection to ensure that the same word would not be presented more than once to each participant. All 6 word lists were matched for average frequency, imagery, and concreteness (Table 2). In the 4-minute retention interval, participants were prevented from rehearsing the words because they were engaged in another cognitively demanding activity, the trail making task (TMT). In the recall phase, participants were handed a blank sheet of paper and had to recall as many words as possible in 2 minutes.

Table 2. Average frequency, imagery, and concreteness of the words in each word list (Friendly et al., 1982).

List #	frequency	imagery	concreteness
1	13.56	5.68	6.00
2	13.44	5.39	5.49
3	13.25	5.60	5.89
4	13.33	5.33	5.70
5	13.22	5.48	5.85
6	13.17	5.44	5.57

Trail Making Task (TMT): The TMT is a neuropsychological test that has been used to study attention, working memory, and inhibitory control (Sánchez-Cubillo et al., 2009). It consists of a sheet of paper that has randomly placed letters and/or numbers. In the "A" version of the task, there are only numbers and participants were asked to trace the numbers in order without lifting the pencil off the paper. In the "B" version of the task, there are both letters and numbers and participants had to once again trace in order but had to alternate between the letters and numbers (i.e. 1, A, 2, B, 3, C, etc). They were instructed to not lift the pencil off the paper and if a mistake was made, they were told to correct it and keep on going. The time to complete each version was noted by the research divers. Each participant completed the TMT twice, once for each dive depth. The time needed to complete version A of the task is taken as a measure of motor control, while the time needed to complete the B version of the task reflects more executive control (i.e., selective attention). The difference in completion time (B – A) divided by the completion time for part A provides a sensitive index of prefrontal cortex functioning (Levine, Miller, Becker, Selnes, & Cohen, 2004; Stuss et al., 2001). A higher proportional index score indicates poorer cognitive functioning.

Profile of Mood States (POMS): We used an abbreviated form of the POMS to measure current mood states. This 40-item survey measured the participant's current mood state in 7 different mood dimensions: tension, anger, fatigue, depression, esteem-related affect, vigor, and confusion (Grove & Prapavessis, 1992).

Participant information survey: We asked each participant about their diving credentials and history, diving concerns, basic demographic information and their general health conditions (i.e., age, height, weight, sea sickness medication use). We also asked them before each dive when they had last consumed alcohol, caffeine, or food and the number of hours slept the night before.

Procedure

All data collection took place on a dive boat off the coast of Fort Lauderdale, FL in the afternoon (American Dream Dive Charters) between the hours of 2 and 3 pm. For practical reasons, all research dives happened over the course of 6 days. Table 3 details the diving conditions and profiles on each day. Participants were required to dive on two separate days and were randomly assigned to a deep or shallow dive on their first day. The deep and shallow dive sites were the same for all participants (Figure 1). The deep dive was, on average, a 27.7 m dive and data collection occurred on a sandy bottom beside a local wreck around 2 pm. The shallow dive was, on average, a 7.4 m dive and data collection occurred on a sandy bottom beside a reef around 3pm. All participant divers dove on a standard air mixture; research divers dove on EANx32.

Table 3. Diving conditions and profiles.

	Shallow Condition				
Date	N	visibility (m)	depth (m)	time at depth (min)	water temp (F)
9-Jul	6	6.7	6.7	16	83
16-Jul	6	7	7	16	84
18-Jul	6	7.6	7.6	14	82
2-Aug	2	7.6	7.6	15	83
7-Aug	4	7.9	7.9	14	83
9-Aug	4	6.1	7.5	14	83
Average		**7.2**	**7.4**	**14.8**	**83.0**
Stdev		**0.7**	**0.4**	**1.0**	**0.6**

	Deep Condition					*Day Conditions*	
Date	N	visibility (m)	depth (m)	time at depth (min)	water temp (F)	air temp (F)	wind (mph)
9-Jul	5	8.2	27.4	25	79	90	E 12
16-Jul	6	9.1	27.7	21	79	88	SSE 12
18-Jul	5	27.4	28	21	68	90	SSE 12
2-Aug	5	21.3	27.7	25	83	87	ESE 15
7-Aug	3	9.1	27.7	19	83	88	ESE 15
9-Aug	3	18.3	27.4	23	82	89	ESE 11
Average		**15.6**	**27.7**	**22.3**	**79.0**	**88.7**	
Stdev		**8.0**	**0.2**	**2.4**	**5.7**	**1.2**	

Before the boat left the dock, all participants signed a consent form and received instructions about the tasks they were going to perform while at depth. The participants were assigned a research diver who would dive with them and collect data while at depth; each research diver collected data from 1 or 2 participant divers at each depth. Underwater data was collected using pencils and waterproof paper on clipboards. Each dive lasted no more than 20 minutes, including a safety stop on the deep dive.

Upon arrival at the dive site, participants first gave a saliva sample. They then entered the water with their research diver and descended to depth. Once there, participant divers filled out the STAI to measure anxiety levels. Next, they were handed a list of 36 words to memorize for 2 minutes. During the subsequent 4-minute retention interval, participants completed parts A and B of the TMT which required attentional control to complete. This task also prevented participants from engaging in rehearsal of the words between the learning and recall phases. After the 4-minute retention interval, participants were given a blank sheet and had to write down all the words from the list that they could remember in 2 minutes. Divers ascended to the surface, completing a safety stop on the deep dive, and boarded the boat. The participants then gave a second saliva sample to record any changes in cortisol levels and completed the POMS to measure current mood state.

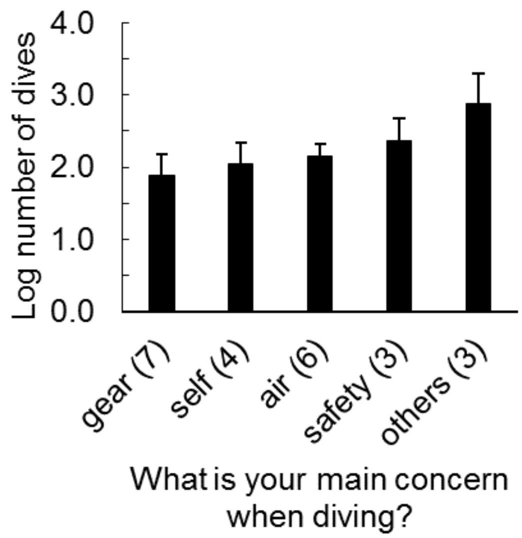
Results

All hypotheses and data analyses were pre-registered with the Open Science Framework and materials have been made publicly available here: https://osf.io/4adk8/. Significance values are two-tailed, unless otherwise noted. We report the means ± standard deviations within the text, effect sizes of significant results using Cohen’s d for the paired t tests, and used an alpha level of .05 to determine significance.

Participant data is displayed in Table 1. Most participants reported being frequent divers with the median number of days since their last dive being 7 and their last deep dive being 21. All participants reported not drinking alcohol in the previous 20 hours before either dive; 12 participants reported drinking caffeine the morning before each dive 2 or more hours before any data was collected. Participants reported statistically similar amounts of sleep the night before each of their dives ($t(22) = 0.175$; $p=0.86$, $d=0.04$). Three participants took sea sickness medicine before both dives. Since participants are serving as their own controls, any effect that the sea sickness medicine has on the cognitive functioning for these divers will be present in both conditions. Two participants took sea sickness medicine before either their deep or shallow dive.

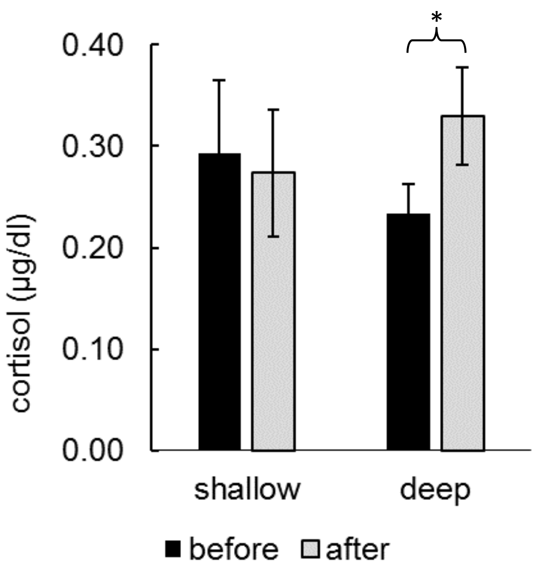
We asked divers about their “biggest concern while diving” and categorized responses into one of five categories based on the divers’ open-ended responses (Figure 2). The most frequent concern divers had was their *gear*, either malfunctioning gear or just forgetting a piece of equipment (N=7). The next most common concern had to do with *air* consumption and whether the diver would have enough air or would run out of air forcing their buddy to surface early (N=6). The next most common concern had to do with the divers’ *physiological state* including whether they would get seasick, whether they would rupture an ear drum, or if they were too cold (N=4). Finally, concerns for *safety* and *concern for others* were both equally reported (N=3). Safety concerns included being hit by the boat and concerns for others had to do with divers being concerned with a fellow diver or marine welfare while diving. Interestingly, as diver experience increased, diving concerns changed from being more self-oriented (diver’s own gear and physiological state) to other-oriented (concerns for safety and others).

Figure 2. Type of concern (N) as a function of the log number of dives the participant has reported being on. Error bars are standard errors of the mean.



We conducted a non-directional paired samples t test on the differences in cortisol levels before and each dive (Figure 3). One participant gave saliva samples that were not readable, possibly because it was contaminated by sea water, leaving 22 participant samples for analysis. We found that cortisol levels were not significantly different before and after a shallow dive ($t(21)=0.58$; $p=.57$; $d=0.13$) but were significantly higher after the deep dive (0.33 ± 0.23 µ/dL) compared to before the dive (0.23 ± 0.14 µ/dL; $t(21)=2.36$; $p=0.028$; $d=0.52$).

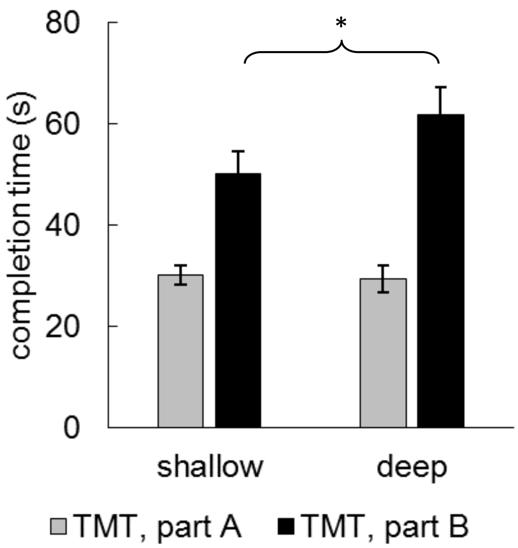
Figure 3. Mean cortisol levels before and after the shallow and deep dives. Error bars are standard error of the mean. * p<0.05



We conducted a directional paired samples t test on the number of correct words obtained in the shallow (8.96 ± 3.83) and deep (7.83 ± 3.03) dives. We found that participants recalled significantly more words when they were diving at the shallow depth ($t(22)=1.86$; $p=.038$, $d=0.39$). There was no significant difference in the number of incorrect words obtained in the shallow (1.13 ± 1.40) and deep (0.78 ± 1.04) dives ($t(22)=1.16$; $p=0.128$).

We conducted a directional paired samples t test on the data obtained in the TMT. The timing from 2 participant divers was lost during ascent after one of the deep dives so this analysis was conducted on the remaining 21 participants. Figure 4 displays the mean time to complete parts A and B of the TMT in the shallow and deep conditions. We found no significant difference in the completion time for part A ($t(20)=0.342$; $p=0.37$), but we did find that the time to complete part B was significantly greater in the deep dive condition (61.71 ± 24.92 ms) compared to the shallow dive condition (50.14 ± 19.80 ms; $t(20)=2.29$; $p=0.02$; $d=0.50$). Finally, we found significantly greater index scores ([B-A]/A) for the deep condition (1.30 ± 1.18) compared to the shallow condition (0.72 ± 0.62; $t(20)=2.79$; $p=0.006$; $d=0.61$).

Figure 4. Mean completion times for parts A and B of the trail making task (TMT). Error bars are standard error of the mean. * p<0.05



We conducted a non-directional paired samples t test on the STAI scores. Two participants missed 1 item and one participant missed 2 items on the STAI. According to the scoring guide, the STAI scores of these participants was pro-rated by calculating the mean score for the items the participant answered, multiplying this value by 20, and rounding up the score to the next whole number (Spielberger et al., 2013). We found no significant difference in the anxiety scores ($t(22)=0.481$; $p=0.635$) between the shallow (26.83 ± 4.76) and deep (27.39 ± 4.93) dives.

Table 4 shows the means, standard deviations, and the results of the non-directional paired t tests for each subscale and the total mood disturbance scores obtained from the POMS. One participant missed one item on the POMS after the deep dive. The item contributed to the tension subscale. The missing item was replaced by the average of the remaining five items that were answered since less than 10% of the items for that subscale were missing. We found no significant differences in any of the mood states (all ps>0.05).

Table 4. Means, standard deviations, and the results of paired t tests for each subscale and the total mood disturbance scores on the POMS. All dfs = 22.

Mood dimension	Depth	Mean	Standard deviation	t	p
Tension	deep	0.97	1.13	-0.27	0.79
	shallow	1.09	1.50		
Anger	deep	0.43	0.84	-0.38	0.70
	shallow	0.52	0.73		
Fatigue	deep	2.96	2.80	1.83	0.08
	shallow	1.83	2.46		
Depression	deep	0.30	0.93	0.44	0.66
	shallow	0.22	0.52		
Esteem-related affect	deep	17.57	2.61	-0.47	0.65
	shallow	17.91	4.17		
Vigor	deep	9.30	3.20	-0.51	0.62
	shallow	9.87	6.03		
Confusion	deep	1.48	1.70	1.25	0.22
	shallow	0.96	1.15		
Total mood disturbance	deep	79.28	7.82	0.94	0.36
	shallow	76.83	11.68		

Discussion

We found that the depth of a dive affected physiological and cognitive functioning. Specifically, at the deep depth, cortisol levels were increased, the number of words remembered was fewer, it took longer to complete Part B of the trail making task which measures attention and working memory, and the prefrontal cortex sensitivity index was greater in the deep dive. In contrast, we found no differences in self-reported anxiety measures, mood measures, or part A of the trail making task which measures simple motor response time.

Diving is a cognitively demanding sport that has been shown to impact memory and attention. Two important factors that could influence poor memory and attention performance are nitrogen narcosis and cortisol levels. Nitrogen is considered an inert gas, in that it is not metabolically processed as quickly as oxygen. When the percentage of nitrogen is reduced in the breathing mixture, as occurs when breathing enriched air nitrox, this reduces the inert gas effect of nitrogen narcosis. Previous studies comparing memory and attention while breathing air or nitrox indicate that cognitive dysfunction can partially be recovered when breathing nitrox (Brebeck et al., 2017; Germonpré et al., 2017). However, these studies did not take into account cortisol levels that are known to rise during diving (Palozzi et al., 2010; Pourhashemi et al., 2016) and impact memory recall.

Increased cortisol levels at the time of memory retrieval negatively impairs performance (Ackermann et al., 2013). Stress-induced cortisol release, via central glucocorticoid receptor activation, is a good candidate as a mediator of the observed impairments in cognitive processing during a deep dive (reviewed in Finsterwald & Alberini, 2014). Cortisol actions in the brain are mediated by mineralocorticoid and glucocorticoid receptors in the hippocampus and the prefrontal cortical structures, regions critical for cognitive processing (De Kloet et al., 1998; Lupien & Lepage, 2001). Working memory and executive function performance can be decreased by stress-induced activation of low-affinity glucocorticoid receptors in the prefrontal cortex (Lupien & Lepage, 2001). Since a critical role of the prefrontal cortex is to reduce distracting or irrelevant information (Wager et al., 2014), it is possible that cortisol-induced impairments in cognition observed in the deep dive condition are due to glucocorticoid receptor mediated increase in distractibility. This interpretation is consistent with our finding that the trail making task proportional index is greater during a deep dive, indicating poorer cognitive functioning.

The cognitive deficits exhibited by participants during the deep dive condition are similar to deficits experienced at high altitude and with dehydration from heat-stress. For instance, Asmaro, Mayall, and Ferguson (2013) found that participants had both impaired motor control and executive control at simulated altitudes of 5334 m and 7620 m respectively. They also found impaired short term and working memory at these altitudes. Gopinathan, Pichan, & Sharma (1988) also found that as level of heat-stress and dehydration increased, participants experienced deficits in both short-term memory and executive control as measured using a word recognition test and the trail-making task respectively. Thus, divers can experience cognitive deficits when diving at deep depths similar to situations and environments we more typically associate with some kind of impairment, and a possible rise in cortisol levels.

The effect of nitrogen narcosis is not often perceived by the diver despite it having deleterious effects on their cognitive functioning. Additionally, stress that is associated with increased cortisol levels, are not perceived during the dive. This is evidenced by our participants not reporting increases anxiety levels on the STAI and POMS despite their increase in cortisol levels. Through the course of their training, divers are taught the dangers of nitrogen narcosis, and while increased practice with diving leads to lower reported anxiety and stress levels, cortisol levels still rise even in experienced divers (Palozzi et al., 2010). The additive effect of these two causes of cognitive dysfunction needs to be studied more to understand how divers can become more self-aware of the issue to ensure diver safety.

We know that some impairments can be overcome with appropriate training and awareness. For example, the more practiced someone is at a task, the fewer errors they make, presumably because the task has become automatic and does not require as many attentional resources (Shiffrin & Schneider, 1977; Logan, 1979). One can see from our limited sample that as diver experience increases, their attentional focus moves away from themselves and onto fellow divers. It is possible that while experienced divers may experience nitrogen narcosis and elevated cortisol levels at equal rates than their less experienced peers, the cognitive dysfunction resulting from nitrogen narcosis could be attenuated because many of the safety behaviors become automatic (i.e. checking air and compass) in experienced divers and so the diver has more attentional resources to devote to other events that happen over the course of a dive. Future research should examine which training protocols lead to automaticity of dive safety behaviors.

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