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Original Article

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Effects of Hyperbaric Nitrogen Narcosis on Cognitive Performance in Recreational air SCUBA Divers: An Auditory Event-related Brain Potentials Study

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Abstract

Background: The narcotic effect of hyperbaric nitrogen is most pronounced in air-breathing divers because it impairs diver's cognitive and behavioral performance, and limits the depth of dive profiles. We aimed to investigate the cognitive effects of simulated (500 kPa) air environments in recreational SCUBA divers, revealed by auditory event-related potentials (AERPs).

Methods: A total of 18 healthy volunteer recreational air SCUBA divers participated in the study. AERPs were recorded in pre-dive, deep-dive, and post-dive sessions.

Results: False-positive score variables were found with significantly higher differences and longer reaction times of hits during deep-dive and post-dive than pre-dive sessions. Also, P3 amplitudes were significantly reduced and peak latencies were prolonged during both deep-dive and post-dive compared with pre-dive sessions.

Conclusion: We observed that nitrogen narcosis at 500 kPa pressure in the dry hyperbaric chamber has a mild-to-moderate negative effect on the cognitive performance of recreational air SCUBA divers, which threatened the safety of diving. Although relatively decreased, this effect also continued in the post-dive sessions. These negative effects are especially important for divers engaged in open-sea diving. Our results show crucial implications for the kinds of control measures that can help to prevent nitrogen narcosis and diving accidents at depths up to 40 msw.

What's important about this paper?

Divers can experience a narcotic effect from breathing nitrogen in compressed air, which can impair cognitive performance and contribute to risk of death. In this study, certified recreational divers experienced simulated dives in a dry hyperbaric chamber. During the simulated deep dive, most participants exhibited mile or moderate signs and symptoms of nitrogen narcosis, including mental dysfunction. During the deep-dive and post-dive, participants exhibited impaired cognitive processing with respect to stimulus evaluation and response selection relative to pre-dive performance. Safe driving beyond 30 msw requires awareness for the delayed effects of nitrogen narcosis.

Keywords: event-related brain potentials; hyperbaric nitrogen narcosis; P3; reaction timessimulated air (40 msw = 500 kPa) diving

Introduction

Diving is an activity during which divers are observed to use complex equipment and specialized skills in an extreme hyperbaric environment for survival. If dive rules are not observed, the diving environment can lead to serious injuries and even fatalities (Ranapurwala *et al.*, 2017), hence it is very important that divers have healthy cognitive functions to mitigate these risks. Compressed atmospheric air is an economic and readily available gas for depths below 30 msw (100 fsw) diving, a possible milieu through which recreational self-contained underwater breathing apparatus (SCUBA) divers prefer to breathe air (Levett and Millar, 2008). There is also a requirement of increased training/certification to use other gas mixtures.

However, almost all breathable gases have a narcotic effect when exposed to various depths and high pressure (Brauer and Way, 1970). The narcotic effect of nitrogen is most pronounced in air-breathing divers because it impairs diver's cognitive performance and limits the depth of dive profiles (see Supplementary Table 1) (Lippmann and Mitchell, 2005; Levett and Millar, 2008; Doolette, 2008). The earliest and most affected site is suggested to be the frontal lobe of the brain, which is responsible for executive functions such as reasoning, memory, learning, perception, decision-making, judgment, attention, and concentration (Petri, 2003; Levett and Millar, 2008). In addition, the most affected areas of the brain include the cerebral cortex, the descending reticular formation, and the basal ganglia, particularly the nigrostriatal pathway, resulting in significant decrease in the levels of striatal glutamate and dopamine (Lavoute *et al.*, 2008; Rostain and Lavoute, 2011).

Although many divers believe they can develop adaptation skills to nitrogen narcosis through practice, some studies reported that habituation reduced subjective symptoms, and cognitive performance remained impaired (Hamilton *et al.*, 1995; Bennett and Rostain, 2002; Buzzacott, 2016). The responses may vary significantly from diver to diver, and even for the same diver on different days (Fairburn, 1993). In addition, nitrogen narcosis induced overconfidence, fixed thinking, and impaired cognitive performance pose an important threat to diver safety. Evidence suggests that many injuries and deaths in which hyperbaric nitrogen narcosis has played a role have occurred in air SCUBA diving (Vann and Lang, 2011; Buzzacott, 2016).

Drowning, which is the usual immediate cause of death, probably accounts for between 57% and 86% of fatalities (Edmonds and Walker, 1989). Drowning is a terminal event, but it is important to explore and identify the potential underlying causes such as loss of consciousness due to a combination of increased work of breathing nitrogen narcosis, oxygen toxicity, and hypercapnia (Lawrence and Cooke, 2006). Nakayama *et al.* (2003) reported that 12.1% of recreational divers showed symptoms of nitrogen narcosis. The Australian and New Zealand (ANZ) diving fatality database (Project Stickybeak) estimated that nitrogen narcosis contributed to almost 9% of reported deaths, but was never the sole cause of death (Edmonds and Walker, 1989). Some international diving agencies seek to lessen the exposure to hyperbaric nitrogen by limiting the depths to which recreational divers can dive without additional training or equipment (Ranapurwala *et al.*, 2014). The British Sub-Aqua Club (BSAC) has always stated that the limit for air diving is 50 msw (160 fsw) only for professional divers, and also recommends the use of helium mixtures (heliox: helium–oxygen or trimix: helium–oxygen–nitrogen) for depths deeper than 30 msw (100 fsw) to avoid nitrogen narcosis (Cumming *et al.*, 2011).

However, today's new trend toward encouraging deep dives may pose a potential danger; therefore, there is a clear need to define a reliable method to demonstrate the potential danger of these limit extensions. Despite the inability of hyperbaric chambers to take into account the effects of cold, immersion, and darkness when testing the effects of nitrogen narcosis, many studies on the effects of narcosis have substituted dry hyperbaric chambers for underwater environments, because they provide a more controlled and safer environment compared with open water. Accordingly, we also used a dry hyperbaric chamber in the present study. Notable differences were reported in the degree of cognitive impairment from the hyperbaric chamber and underwater environments, even when the effects of simply being underwater were controlled (Hobbs and Kneller, 2011; Balestra *et al.*, 2012; Hobbs *et al.*, 2014; Steinberg and Doppelmayr, 2017). Although the effects of nitrogen narcosis on cognitive performance in divers have frequently been reported in hyperbaric chamber dives at different depths below sea level and gas mixtures (Harding *et al.*, 2004; Meckler *et al.*, 2014), there are few event-related potential (ERP) studies (Fowler *et al.*, 1990; Wada *et al.*, 1991; Fowler *et al.*, 1993; Philipova, 1998).

ERPs are the electroencephalogram (EEG) changes that are time-locked to events consisting of the sensory, motor or cognitive domains. ERPs provide a safe and non-invasive method of studying brain neural activity in response to a stimulus with precise temporal high-resolution reflecting the speed of cognitive processes (Handy, 2005). P3 is a positive potential that occurs approximately 300 ms after a response to target (random and rare or unexpected) stimulus onset and has scalp distribution maximal over centro-parietal electrodes in the auditory modalities. P3 latency is suggested to reflect cognitive processing speed and/or evaluating perceptual information, and P3 amplitude is suggested to reflect the evaluation of a stimulus with respect to action planning. It is commonly thought to reflect the amount of working memory updating and the orienting of attention (Donchin and Coles, 1988; Polich, 2004).

The P3 wave has been the most widely studied oddball ERP component for investigating cognitive processes in patients with neurologic (Uslu *et al.*, 2020) and psychiatric (Demiralp *et al.*, 2002) diseases as an index of selective attention and working memory processes. P3 has also been used by several researchers to investigate the cognitive impairment in divers caused by silent bubbles (Ergen *et al.*, 2017) and nitrogen narcosis (Fowler *et al.*, 1990, 1993; Wada *et al.*, 1991; Philipova, 1998). Although auditory oddball (button press of targets) tasks do not exactly mimic the actual tasks a diver is required to perform during diving, collected ERP data show explicit indications of the levels of cognitive impairment that a diver can develop in deep-dive and post-dive sessions.

We hypothesized that (i) in diving with compressed air, nitrogen narcosis would affect the brain neural activity and cause cognitive and behavioral performance impairment in divers, (ii) that this could be precisely assessed by auditory event-related potentials (AERPs), and (iii) recreational air SCUBA diving extended up to 40 msw might be a risk for nitrogen narcosis for the divers.

This study aimed at investigating the possible cognitive effects caused by a hyperbaric air (40 msw = 500 kPa) environment and nitrogen narcosis in recreational SCUBA divers as revealed by comprehensive AERPs.

Methods

Participants

This study was conducted in line with the tenets of the Helsinki Declaration. The project received approval from the Ethics Committee of the Istanbul Faculty of Medicine. Each participant was informed of the purpose of the study, experimental diving, and the AERP recording procedure before being registered for the study. Subsequently, all participants provided written informed consent.

All divers had a minimum qualification of *Confédération Mondiale des Activités Subaquatiques (CMAS)* 1-star SCUBA diver. The divers were examined by a physician qualified in diving medicine. All participants were reported to be in the good physical condition and were not on any medication. All divers were then asked to carefully and as accurately as possible, complete a detailed questionnaire about their demographic information such as age (years), education (years), body mass index (BMI), the status of smoking and alcohol consumption, diving history including diving certificates, years of diving experience, the total number of dives, average depth (msw), average bottom time (min), deepest dive meter (msw), and longest dive time (min).

Data acquisition and analysis*

Auditory event-related potentials (ERPs) recording

The participants sat in hyperbaric chamber (HyperTech ZYRON 12, Multiplace Chamber Systems, Istanbul, Turkey) which was dimly lit. EEG EEG signals were recorded from nine scalp electrodes according to the international 10/20 system (Brainard, 1997).

AERP stimuli and procedures

The cognitive functions of the participants were evaluated using the auditory oddball paradigm, which focuses on selective attention and executive functions. AERPs are obtained via a simple discrimination task, known as the classic oddball paradigm (Katsarou *et al.*, 2004; Luck *et al.*, 2000) The AERP recording systems were located inside and outside the hyperbaric chamber (see Fig. 1).

Simulated air dive procedure and profile

All dry-dive simulation profiles were performed in accordance with the *U.S. Navy Diving Manual, Revision 7, Air Decompression Table* (U.S. Navy, 2016) (see Fig. 2).

Behavioral performance and AERP analysis*

Behavioral performance was evaluated as the reaction times (RT) of the 'Hits', 'false positives', and 'misses'. The grand averaged AERPs were inspected to observe whether any ERP waves differed between the groups, and if any wave seemed to differ, the time-windows for peak measurements were roughly determined based on the grand averages (see Fig. 3).

Statistical analyses*

The statistical analysis of the RTs, miss, and false positives of the AERP task performance were as follows: parametric one-way analysis of variance (ANOVA) was performed with Bonferroni corrected pairwise session comparisons and non-parametric Friedman test with Dunn–Bonferroni post-hoc comparisons were used. The differences in amplitude and latency (N1, P2, N2, P3) waveforms were analyzed using a repeated-measures ANOVA and post-hoc analysis with Bonferroni correction was used for the comparison of pairwise conditions.

Data acquisition and analysis*, Behavioral performance and AERP analysis*, and Statistical analyses* methods were explained to more detail in Supplementary Text 1 (Ergen *et al.*, 2017; Uslu *et al.*, 2020).

Results

The participant's profile

A total of 20 right-handed healthy male volunteer recreational SCUBA divers were enrolled in the study. However, two participants were excluded due to excessive artifacts (e.g. eye-blink, eye movements, face, and body muscle activity) in their AERP recording data caused by nitrogen narcosis during the in deep-dive session. EEG data of the remaining 18 participants were quite adequate and analyzable. Their ages were between 22–35 years, and the mean age was 27 years. The results of the demographic characteristics and diving history of the divers are presented in Table 1.

The participants were asked for any behavioral and cognitive effects caused by nitrogen narcosis in the

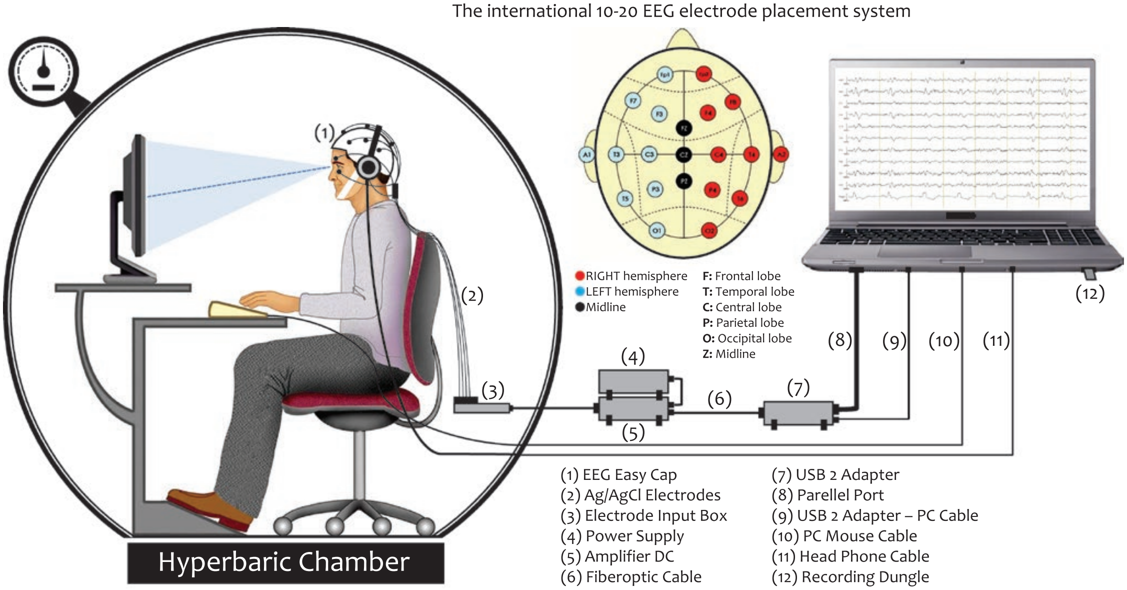

Figure 1. Schematic diagram of the AERPs recording system setup.

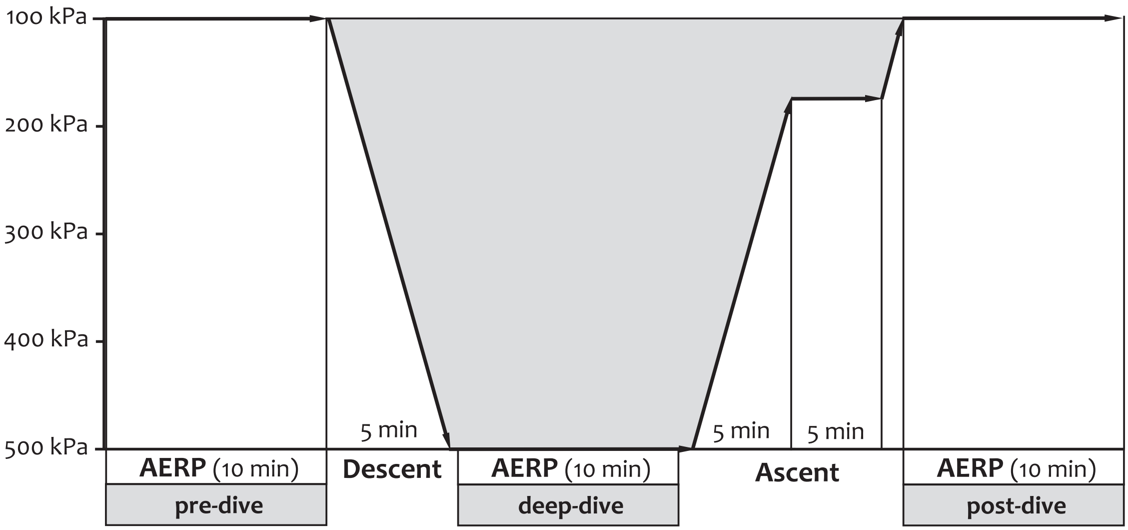

Figure 2. The AERP recording sessions and simulated dive profiles.

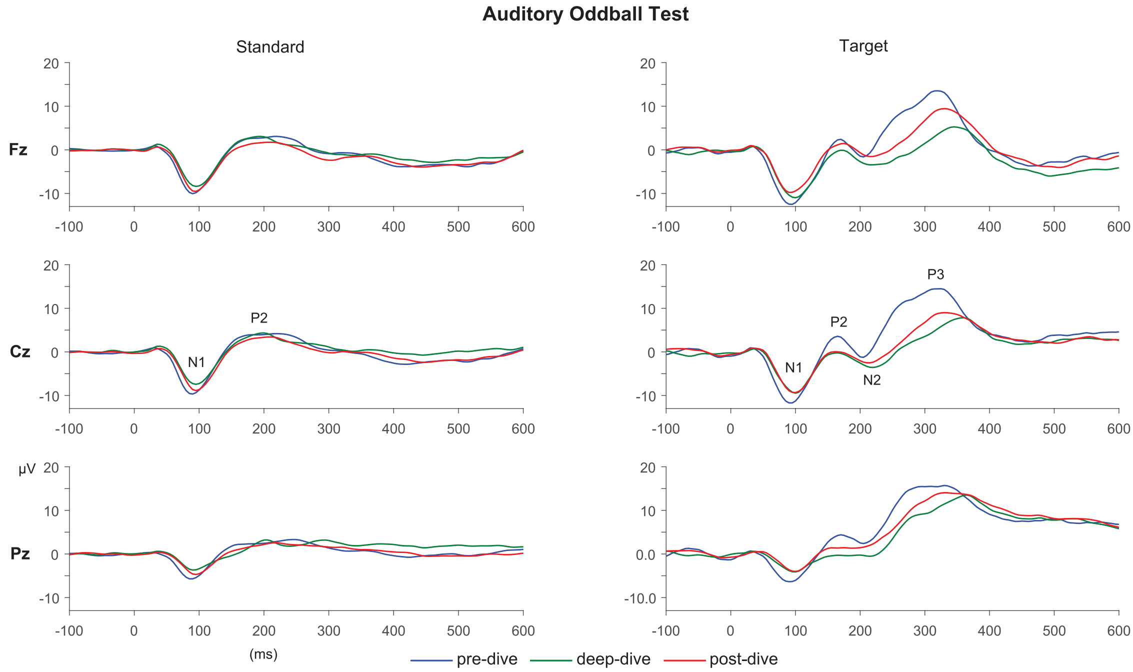

Figure 3. The grand averages of AERP waveforms from midline (Fz, Cz, Pz) electrodes.

deep-dive and post-dive sessions. Most participants manifested mild or moderate signs and symptoms of the first level of nitrogen narcosis, including mental dysfunction (i.e. light-headedness and euphoria, retardation of decision-making) during the deep-dive (500 kPa) session. In addition, some participants reported dizziness, finger tremor, and inattention during the deep-dive session; however, these symptoms were mild and disappeared following the session.

Behavioral performances

The number of false-positive button presses (mouse-button click made after a standard stimulus) were found to have a significant condition (or session) effect (χ^2 (2) = 16.270, $P < 0.001$, $W = 1.810$), and post-hoc comparisons revealed that this effect resulted from the deep-dive versus pre-dive session ($P = 0.014$). However, these were not found in deep-dive versus post-dive sessions. Similarly, there were no significant differences as for the number of missed targets (missed mouse-button clicks for a target) among the three sessions.

In addition, we found significant condition effects in the mean RTs of 'hits' (mouse-button clicks done after the target stimulus), (F (1.47) = 47.816, $P < 0.001$, $\eta^2 = 0.738$). Pairwise post-hoc comparison tests showed RT clearly prolonged in deep-dive (28.5 ms) and post-dive (18.3 ms) compared with pre-dive sessions ($P < 0.001$ for both comparisons), and similarly deep-dive (10.2 ms) compared with the post-dive session ($P = 0.003$). The results of behavioral performance in AERP paradigms are presented in Table 2.

Table 1. The demographic characteristics and diving history of the divers.

Participants ($n = 18$)	Mean
Age (years)	27
Education (years)	19
Body mass index (BMI)	23
Status of smoking consumption (n)	
• *Never smoker*	*12*
• *Former smoker*	*4*
• *Current smoker (5–10 cigarettes per day)*	*2*
Status of alcohol consumption (n)	
• *Never consumed*	*9*
• *Former consumed (social drinker)*	*5*
• *Current consumption (rarely)*	*4*
SCUBA diving (*CMAS) certified (n)	
• *CMAS trainers*	3
• *CMAS 1 star*	6
• *CMAS 2 star*	5
• *CMAS 3 star*	4
Diving experience (years)	4
Total number of dives	96
Average depth (msw)	24
Average bottom time (min)	36
Deepest dive (msw)	41
Longest dive time (min)	5

*CMAS: Confédération Mondiale des Activités Subaquatiques.

Auditory event-related potentials

The results of the AERP standard and target stimulus were as follows: in the target, there was a significant condition effect on the N1 peak amplitude (F (2,34) = 7.009, $P = 0.005$, $\eta^2 = 0.292$), whereas the pairwise post-hoc comparisons demonstrated that the N1 amplitude was less negative (i.e. lesser amplitude) in deep-dive than in pre-dive ($P = 0.012$) and post-dive sessions ($P = 0.005$).

Another significant condition effect was monitored on target P2 peak amplitude (F (2,34) = 10.067, $P = 0.002$, $\eta^2 = 0.372$); post-hoc comparisons demonstrated that the N1 amplitude was smaller during the deep-dive versus pre-dive ($P = 0.005$), and the post-dive versus pre-dive sessions ($P = 0.007$).

Target N2 peak amplitude measures also revealed crucial condition effects (F (2,34) = 4.876, $P = 0.016$, $\eta^2 = 0.223$), while the pairwise post-hoc comparisons showed that the target N2 amplitudes were more negative during the deep-dive when compared with the pre-dive sessions ($P = 0.049$).

There was also significant group effects on target N2 latency showed significant group effects (F (2,34) = 5.074, $P = 0.015$, $\eta^2 = 0.230$). In addition, N2 latency both of deep-dive and post-dive sessions were significantly longer compared with pre-dive sessions ($P = 0.026$ and $P = 0.029$, respectively).

Analyses of the target P3 wave showed important condition effects on both amplitude (F (2,34) = 18.767, $P < 0.001$, $\eta^2 = 0.525$) and latency (F (2,34) = 7.558, $P = 0.002$, $\eta^2 = 0.308$). The succeeding post-hoc comparison

Table 2. The results of behavioral performance in AERP paradigms.

Auditory oddball test	Pre-dive	Deep-dive	Post-dive	F	P	W/η^2
‡ Misses (score)	0–1 (0)	0–1 (1)	0–1 (1)	6.500	0.059	–
‡ False positives (score)	0–1 (1)	1–2 (1)	0–1 (1)	16.270*	<0.001	1.810 ^{W}
‡‡ Mean RT of hits (ms)	319.7 ± 89.1	348.2 ± 107.4	338.0 ± 46.1	47.816*	<0.001	0.738 η^2

‡Related-samples Friedman's two-way analysis of variance test was carried out and (χ^2) reported with as Q1–Q3 (median) where Q1: first quartile, Q3: third quartile.

‡‡ One-way ANOVA was carried out and F ratio reported with mean ± standard deviation.

W: Kendall's W effect size; η^2: partial eta squared; *$P < 0.001$.

Table 3. The results of AERP amplitude (μV) and latency (ms) in the oddball task.

AERPs	Amplitude						Latency					
	Pre-dive	Deep-dive	Post-dive	*F*	*P*	η_p^2	Pre-dive	Deep-dive	Post-dive	*F*	*P*	η_p^2
Standard												
N1	−7.2 ± 2.7	−5.7 ± 2.9	−6.8 ± 2.6	2.068	0.142	–	94.1 ± 9.7	99.2 ± 12.0	96.9 ± 11.1	1.390	0.263	–
P2	3.1 ± 1.5	2.8 ± 1.7	3.2 ± 2.1	0.329	0.713	–	176.5 ± 24.0	184.7 ± 19.7	183.8 ± 24.5	1.018	0.364	–
Target												
N1	−9.9 ± 2.7	−8.1 ± 3.6	−7.4 ± 2.8	7.009*	0.005	0.292	97.0 ± 11.9	101.6 ± 17.9	99.4 ± 14.2	0.736	0.478	–
P2	3.4 ± 2.4	−0.1 ± 4.3	1.6 ± 3.3	10.067*	0.002	0.372	167.4 ± 14.6	170.1 ± 27.2	172.4 ± 23.5	0.534	0.543	–
N2	−0.8 ± 3.1	−2.5 ± 3.2	−1.2 ± 2.5	4.876*	0.016	0.223	208.2 ± 20.6	230.1 ± 28.7	226.6 ± 24.5	5.074*	0.015	0.230
P3	14.5 ± 4.6	8.6 ± 3.8	11.6 ± 4.0	18.767**	< 0.001	0.525	312.9 ± 32.1	342.8 ± 34.2	336.0 ± 27.4	7.558*	0.002	0.308

Repeated measures ANOVA was carried out, *F* ratio was reported with mean ± standard deviation.
$^*P < 0.05$; $^{**}P < 0.001$; η_p^2: partial eta squared.

of the results was as follows: the target P3 peak amplitude during pre-dive was higher than during deep-dive and post-dive sessions ($P < 0.006$ and $P = 0.047$, respectively), and similarly, during the deep-dive and post-dive sessions ($P = 0.024$). In addition, P3 latencies of deep-dive and post-dive sessions were clearly found to be prolonged compared with the pre-dive session ($P = 0.006$ and $P = 0.038$, respectively). However, no significant differences were found in either the N1 and P2 amplitudes and latencies of standard stimuli between the three sessions (see Fig. 3 and Table 3).

Discussion

The current study shows significant differences in both target N1 (less negativity) and P2 (lower positivity) amplitudes in response to target stimuli, which implies poorer attention allocation to the target both during the deep-dive and post-dive sessions than during the pre-dive session. However, no such differences were found in N1 or P2 latencies (see Fig. 3 and Table 3).

For both of the ERP components, it seems that the target N2 and P3 waveforms are closely associated with the cognitive processes of perception, stimulus categorization, and selective attention. N2 also occurs under oddball target task conditions, during which the participant deliberately focuses on deviant stimuli (Donchin, 1981). We found significant differences in smaller target N2 amplitudes and prolonged latency during both the deep-dive and post-dive sessions compared with the pre-dive session (Table 3). The N2 amplitudes suggested impairment of inhibition in the divers, during both deep-dive and post-dive sessions.

The prolonged N2 and P3 latencies, and delayed RT suggested impaired cognitive processing in terms of the stimulus evaluation and response selection. The oddball P3 wave is the most important and widely used ERP component for studying cognitive functions in many neurologic (Uslu *et al.*, 2020) and psychiatric diseases (Demiralp *et al.*, 2002). It has also been used by several researchers to investigate the cognitive impairment of divers caused by nitrogen narcosis (Fowler *et al.*, 1990, 1993; Wada *et al.*, 1991; Philipova, 1998). P3 is obtained in response to processing relatively rare and random target stimuli, mental counting of targets or cognitive processing. The P3 wave displays typical scalp topography with maximum over centro-parietal electrodes, which is generally named as P3b. This waveform represents a higher cognitive function of information processing, stimulus categorization, or working memory (Kutas *et al.*, 1977; Fowler *et al.*, 1983; Polich, 2004, 2007). It is also generally acknowledged that the P3 wave reflects the timing of cognitive processes but is not correlated with RT (Fowler *et al.*, 1983).

It is widely accepted in the literature that N1 and P2 waves are early components, whereas N2 and P3 waves are late components of ERP (Kok, 1997). Components of the auditory N1, P2, and N2 waves were reported to be related to cognitive processes of selective attention (Luck, 2000), and to reflect the sensory processing of the stimulus by the auditory cortex (Sur and Sinha, 2009). AERPs were obtained using a simple auditory oddball stimulus discrimination task, which yielded significant differences in amplitudes and/or latencies of N1, P2, N2, and P3 waves between the three sessions. Most differences in target AERPs were found between pre-dive and deep-dive sessions.

The N1 wave is observed when faced with an unexpected stimulus. It is an orienting response or a ‘matching process’. In other words, whenever a stimulus is presented it is matched with previously experienced stimuli. The N1 response reaches maximal amplitudes at the Cz electrode (Crowley and Colrain, 2004). The auditory ERP-P2 waveform is usually reported to be the end of the N1–P2 complex or the 'vertex potential'. This waveform is also assumed to reflect the withdrawal of attention from the stimulus after the classification process is completed (Dempster, 1991; García-Larrea *et al.*, 1992). The effect is more pronounced in the frontal area and probably based on the frontal mechanisms, which hinder the interference of the task-irrelevant stimulus (Näätänen, 1990).

Nitrogen narcosis is known to impair sensorimotor information processing, prolongs both RT and P3 latency, and increases false-positive and miss scores (Fowler *et al.*, 1983, 1990, 1993; Wada *et al.*, 1991; Philipova, 1998;). In a study by Fowler *et al.* (1983), nitrogen narcosis was induced in two different experimental designs. First with compressed air with the use of a hyperbaric chamber at atmosphere absolute (ATA), and second with 35% N_2O–65% O_2, and was performed using a serial choice response time task. Identical impairment in cognitive performances were reported in both breathing mixtures. A slow down of response latency and an increased number of errors were reported. However, the mechanisms involved and the locus of this effect have yet to be concluded. In a visual oddball ERP study by Fowler *et al.* (1990), subjects were subjected to breathing air or a non-narcotic heliox (80% He–20% O_2) gas mixture in a hyperbaric chamber at 6.5, 8.3, and 10 ATA. A strong relationship was observed between RT and P3 latency, both of which were found to be prolonged related to the dose amount by hyperbaric air, but not by heliox. However, they found no precise dose-response relationship for the P3 amplitude.

In an auditory oddball ERP study conducted by Wada *et al.* (1991), which investigated the simulated underwater environment in hyperbaric chamber dives at 19 ATA with heliox, it was reported that, unlike amplitude, P3 latency was clearly prolonged and continued to 70 m below sea level. However, their study was performed with only two divers. Philipova (1998) investigated auditory information processing of the divers during pre-diving and decompression sessions from hyperbaric trimix gas mixture conditions using AERP and sensorimotor reaction time. Philipova reported that the sensorimotor reactions, N2, and P3 latency were prolonged during the decompression session, and suggested that this series gave grounds to acceptance of cognitive slowing that takes part in the longer RTs during decompression session.

Diving-related cognitive impairment was also observed by Lafère *et al.* (2019), when breathing either air or enriched air nitrox (40% O_2–60% nitrogen) during two dry chamber dives up to 0.4 MPa. Their assessment was based on behavioral computer-based testing psychology experiment building language and critical flicker fusion frequency while continuously recording brain oxygenation with near-infrared spectroscopy. Slightly different results at higher depths and breathing mixtures were also obtained by Rocco *et al.* (2019). For further investigation of this subject, brainstem evoked potentials instead of cortical evaluations might be interesting (Germonpre et al., 2017; Brebeck *et al.*, 2017).

In the present study, we observed a lower P3 amplitude, and P3 latency and clearly prolonged RT during both deep-dive and post-dive sessions compared with the pre-dive session (see Table 3). Our P3 results were found to be compatible with impairment in cognitive processing of information; the decrease in the intensity of the processes of selective attention and asynchrony in the activation of generators of these potentials in divers (especially pre-dive versus deep-dive, and relatively pre-dive versus post-dive sessions) were related with cognitive dysfunction. RTs appear to be affected by increasing depth during deep-dive sessions; nevertheless, it is not clear whether it stems from the neuromuscular deficit, cognitive dysfunction, or the direct effect of pressure on the neurons.

We found that behavioral performances including the number of false-positive scores were higher, especially during the deep-dive compared with the pre-dive session. However, there were no significant differences in the number of missed button presses among the three sessions (see Table 2). The behavioral (misses and false positives scores) and AERP (N2 and P3 waves) data indicate that the divers had selective impairment of inhibitory function and that this deficit might result from impaired inhibitory executive function in the frontal lobe. These impairments can be attributed to the dysfunction of multiple systems related to the injury process in divers, which are not necessarily related to motor symptoms.

Although nitrogen narcosis is claimed to be completely reversible within several minutes by ascending to a shallower depth (Emerson, 2002), Balestra *et al.* (2012) and Germonpré *et al.* (2017) reported that cognitive impairment continued after surfacing from in-water dives by recreational divers. Our findings are consistent with their results. We also observed that nitrogen narcosis at 500 kPa pressure in the dry hyperbaric chamber had a mild-to-moderate negative effect on the cognitive performance of recreational air SCUBA divers, which threatened the safety of diving, and although relatively decreased, this effect also continued in the post-dive session. These negative effects are especially important for divers engaged in open sea diving.

Conclusions

All dives can be dangerous if dive rules are not observed. Diving with air beyond 30 msw is not prudent and can be a threat to diver safety because of nitrogen narcosis. Safe diving beyond 30 msw requires an awareness of the ever-increasing risk of this condition and its effects on cognitive performance and judgment of divers. In addition, our results could present important implications for the kinds of control measures to be taken to avoid diving accidents at depths up to 40 msw. We suggest that diving agencies in particular need to take into consideration depths up to 40 msw and the delayed effects of nitrogen narcosis and add these to their curriculum.

In conclusion, our present AERP study contributes to the current knowledge about the negative effect of nitrogen narcosis on cognitive performance in recreational air SCUBA divers below 40 msw (500 kPa). The P3 component of ERP is a handy tool and a valuable neuro marker for the detection of these effects.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

Supplementary Table 1. The signs and symptoms of nitrogen narcosis at different depths.

Supplementary Text 1. Data acquisition and analysis*, Behavioral performance and AERP analysis*, and Statistical analysis methods*.

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Conflict of Interests

The author(s) declared no potential of interest (personal, academic, sources of financial/nonfinancial and/or material support, corporate involvement, and patent holdings, etc.) regarding this article.

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