The Effect of Acute Breath-Holding Exercise in Different Conditions on Cognitive Performance in Free Divers

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Abstract

There is a growing trend towards studying human cognition in aquatic environments. At present, there exists a dearth of scholarly investigations pertaining to the immediate effects on executive functions subsequent to a solitary breath-holding training session within the cohort of professional free divers who engage in highly strenuous activities that test their physiological boundaries. The objective of this study was to investigate the immediate impact of breath-holding exercises conducted in varying environments (water and land) on the executive functions of professional diving athletes. The research comprised a sample of 18 male individuals engaged in competitive free diving. The experimental design encompassed four distinct sessions: i) an initial phase dedicated to familiarising participants with the N-back test; ii) a subsequent phase involving the collection of baseline and control measurements for the N-back test; iii) a session focused on obtaining anthropometric measurements; and iv) a final session dedicated to measuring lung capacity. The cognitive assessments were conducted subsequent to the breath-holding exercise protocol, which occurred subsequent to both the land and water sessions. The results indicated a significant difference in reaction times between breath-holding exercises conducted on land and in water ($p = .021$). The computation of delta values was employed to ascertain alterations in cognitive test outcomes under distinct conditions (water and land) in comparison to the control condition. The findings revealed a statistically significant decline in cognitive performance in the water condition relative to the land condition (z:-2.025, p= 0.043, r= -0.544). This study claims that the implementation of breath-holding exercise training in surface water conditions among divers could potentially result in adverse effects on executive functions. Moreover, it has been observed that the identical breath-holding exercises, when executed in terrestrial environments, exhibit a moderate enhancement of executive functions. The present study posits that the aforementioned findings will make a valuable contribution to the development of training methodologies for athletes and coaches involved in the discipline of freediving. Additionally, these findings are anticipated to offer valuable insights into the physiological well-being of divers.

Keywords: Free Diving, Executive Function, Breath-Hold Exercise, Reaction Time

1. Introduction

The physiological changes that occur during exercise, both acute and chronic, have been extensively documented and acknowledged within the scientific community. In recent years, researchers have directed their attention towards investigating the impact of exercise on brain functions and cognitive abilities. They have endeavoured to elucidate the underlying physiological mechanisms that account for the observed changes (Bediz et al., 2016; Günay et al., 2019; Manci et al., 2023). The available research findings suggest that engaging in a single session of aerobic exercise on a treadmill or cycle for a duration of 25 minutes has been shown to have immediate positive effects on attention and executive functions (Netz et al., 2016; Zimmer et al., 2016). Several neuroimaging studies have been conducted to investigate the underlying mechanisms, and it has been argued that the augmentation of brain blood flow serves as an indicator for enhanced cognitive functions (Herold et al., 2019; Perrey, 2020). Conversely, scholarly discourse has also examined the impact of heightened arousal and elevated catecholamine levels resulting from acute exercise on cognitive enhancement (Anish, 2005; Chmura et al., 1994).

The investigation of the immediate physiological and performance impacts resulting from exercise conducted in varying environmental conditions is a topic of interest. The human physiology demonstrates acute changes based on environmental conditions. Engaging in physical exercise leads to outcomes that are significantly different from those observed under typical circumstances (Wilmore et al.,

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2004). The research findings suggest the occurrence of disruptions in brain blood flow during aerobic exercises performed in hypoxic conditions (Curtelin et al., 2018). In contrast, an examination of the immediate impacts of aquatic exercise reveals that cognitive functions influenced by the combined effects of water and physical activity exhibit enhancements attributable to enhanced blood circulation (Türkmen et al., 2022).

Diving athletes challenge their physiological boundaries by exposing their bodies to extended periods of oxygen deprivation as well as the elevated pressure encountered at different depths. The present maximum duration of breath-holding for a diver in a prone position in a swimming pool is 9 minutes and 2 seconds for female divers and 11 minutes and 35 seconds for male divers, specifically in the context of static apnea. Upon initiation of breath-holding while on the water's surface, alterations in the overall cardiovascular dynamics, specifically in cardiac output, become evident. The primary factor contributing to this phenomenon is the eradication of the gravitational impact resulting from immersion in water (Lindholm & Lundgren, 2009). Various responses in cerebral blood flow can be observed when an individual is submerged in water, depending on hydrostatic pressure and water temperature (Worley et al., 2021).

According to existing scientific literature, it has been observed that alterations in cerebral blood flow can occur as a result of elevated levels of oxygen or carbon dioxide pressure. Furthermore, it has been established that instances of diminished carbon dioxide exposure are particularly observed in situations such as hyperventilation during diving (Patrician et al., 2021). The experience of extreme stress can result in the concurrent activation of physiological responses that differ significantly from those observed during moderate aerobic exercise. Consequently, it may lead to notable acute differences when compared to alternative forms of exercise. The available research findings suggest that individuals involved in scuba diving may experience impaired executive functions, with the extent of impairment potentially varying based on the depth of the dive (Möller et al., 2023; Steinberg & Doppelmayr, 2017). On the other hand, it is noteworthy to mention the conspicuous lack of scholarly literature pertaining to athletes involved in breath-hold diving.

It is important to highlight that, as far as our understanding goes, there is a lack of scholarly investigation regarding the immediate cognitive reactions of breath-holding freediving athletes in response to stimuli induced by training. The insufficiency of research focusing on specific populations, such as male diving athletes, underscores the necessity for additional inquiry. The objective of this study is to examine the immediate impact of breath-hold training on cognitive characteristics among male professional diving athletes. The primary conjecture of our study posits that the performance of executive functions may be compromised following acute breath-hold exercise in an aquatic environment, as compared to exercise conducted on land.

2. Materials and Methods

2.1 Subjects

The study included 18 male participants (age: 19.55 ± 2.89 years; body height: 172.2 ± 8.53 cm; body weight: 68.6 ± 10.26 kg), the participants had an average training experience of 7 years. All participants who were registered met the specified general criteria for inclusion. The inclusion criteria for participants in this study were as follows: (i) individuals aged between 18 and 26 years; (ii) individuals without any symptoms of depression; (iii) individuals without any history of injuries; (iv) individuals who maintained a regular training regimen; and (v) individuals without any pre-existing neurologic, psychiatric, orthopedic, or cardiovascular diseases, and who did not take any medications during the study period. All participants who did not meet the predetermined inclusion criteria were excluded from the present study. The Power 3197 software was employed to ascertain the number of participants. The study's effect size, which was computed using variance analysis in the G-Power programme, was found to be 0.7. The study's minimum required sample size was determined to be 9 individuals, based on an alpha error rate of 5% and a power of 95%.

Prior to the commencement of the study, all participants were extensively briefed on the specific objectives of the research. Subsequently, they expressed their consent to participate by duly completing a consent form, thereby indicating their informed agreement to partake in the study. The study was granted approval by the Ethics Committee of Trakya University, with the reference number TUTF-GOBAEK 2023/248, and adhered to the guidelines set forth in the Helsinki Declaration of 2004.

2.2 Experimental Design

The experiments were carried out over the course of four sessions. During the inaugural session, participants were provided with information and introduced to the protocols of the N-Back test. During the familiarisation session, the participants were provided with verbal instructions regarding the 2-back cognitive task and were directed to complete the test on two separate occasions. After a span of two days, all participants were present for the control session. During this session, various assessments were conducted, including the baseline 2-back Test, anthropometric measurements, and lung capacities.

After a period of two days, the participants were assigned in a random manner to complete both sessions involving water and land. In a parallel manner, subsequent to a lapse of two days for recuperation, the participants proceeded to conclude the session in which they had not previously engaged. The researcher conducted all tests, while the design and implementation of the breath-holding protocol were performed by a coach at the National level.

The scheduling of all sessions occurred within the time frame of 4:00 PM and 6:00 PM. The cognitive tests were conducted using an identical computer model. The participants were provided with instructions to abstain from participating in vigorous physical activity within the preceding 24-hour period in order to ensure that they were sufficiently rested. Throughout the water testing procedures, the water temperature was consistently regulated within the range of 26–27 degrees Celsius. In addition, participants were instructed to refrain from consuming alcohol and caffeine within the preceding 24-hour period and to prioritise adequate hydration prior to the administration of the tests. Furthermore, the study incorporated individuals who had experienced a sleep duration of six hours or less on various nights.

2.3 Anthropometric Measurements

The height was assessed during the phase of mid-inspiration utilising a portable stadiometer (Seca, model 217, Hamburg, Germany) with a precision of 0.5 cm. The measurement of body mass index (BMI) was conducted utilising a calibrated electronic scale (Seca, model 875, Hamburg, Germany). The weight measurements of the participants were obtained in a poolside setting, with participants being barefoot and wearing solely swimwear. The Body Mass Index (BMI) was computed by dividing an individual's mass by the square of their height (mass/height^2). The mass was measured in kilogrammes (kg) and the height was recorded in metres (m), (Giles et al., 2014).

2.4 Lung Capacity Measurements

The researchers used a Ganshorn Medizin Electronic Niederlauer, Germany-made Spiro Scout spirometer with an ultrasonic sensor to conduct the measurements (Figure 1a) (Guerriero et al., 2015). The tests were performed in accordance with the acceptability criteria outlined by the European Respiratory Society (ERS, 2005) (Bernhardsen et al., 2022; Laursen et al., 2021). The participants were provided with comprehensive information regarding the measurement procedures. Participants were given explicit instructions to facilitate their navigation through the testing procedure, and they were motivated to adhere to these instructions at every stage in order to maintain appropriate breathing technique (Akpinar-Elci et al., 2006; Miller et al., 2005; Sim et al., 2017).

The test manoeuvres were iterated a minimum of three times while in a stationary stance, and the maximum recorded value was chosen. In order to offer assistance in the event of participants experiencing dizziness during measurements Miller et al. (2005), positioned a chair behind them. Valid tests were only those that exhibited less than 5% variability and were reproducible. The participants were provided with instructions to perform a complete inhalation in order to maximise the utilisation of their entire lung capacity. Subsequently, they were instructed to exhale through a nozzle until reaching the point of residual volume. In the study, participants were instructed to perform forced vital capacity (FVC) measurements.

Specifically, they were directed to create an airtight seal with their lips around the mouthpiece subsequent to taking a maximal breath. Subsequently, participants were required to exhale in a controlled and uniform manner until there was no observable change in volume, with a tolerance of ±0.025 L, for a duration of 1 second (Miller et al., 2005). During the entirety of the experiments, the participants were equipped with a nose clip (Diniz et al., 2014; Miller et al., 2005).

2.5 Breath Hold Exercise Protocol

The protocol consists of two session (warm-up and breath-hold training) and is completed in approximately 40 minutes.

2.6 Warm-up Session

Before breath-hold exercise sessions in both W-land and aquatic environments, a 10-minute standard warm-up protocol was administered (Figure 1b).

- 30 seconds breath hold, followed by 30 seconds of breathing.
- 1 minute breath hold, followed by 1 minute of breathing.
- 2 minutes breath hold, followed by 2 minutes of breathing.
- 1 minute breath hold, followed by 1 minute of breathing.
- 30 seconds breath hold, followed by 30 seconds of breathing.

2.7 Training Session

After a 5-minute transition period following the warm-up, breath-hold loads equivalent to 50% of participants' their official best time durations were determined (https://tssf.gov.tr/tssf-yarisma-sonuclari/). Between each repetition, a progressive load was applied consisting of 1/2 and 1/1 work/rest ratios, totalling 2 sets (4 repetitions). Participants completed this session in approximately 25 minutes.

In order to mitigate the influence of pressure, experiments were conducted in underwater settings at the surface of the water (Figure 1). Muscular activity was minimised across all conditions in order to mitigate exercise-induced oxygen consumption. During the initial phase of the resting period, participants exhibited a regular respiratory pattern. Before entering the shallow dive phase, the individuals in question engaged in a respiratory process known as Total Lung Capacity, wherein they took a breath. Following this, they proceeded to execute their final breaths through a series of partial and deliberate exhalations. This involved inhaling deeply over a span of four beats, followed by a slow exhalation lasting eight beats. The utilisation of the hyperventilation breathing technique was deliberately omitted. The participants employed a nasal clip during both the warm-up and primary exercise sessions across all experimental conditions.

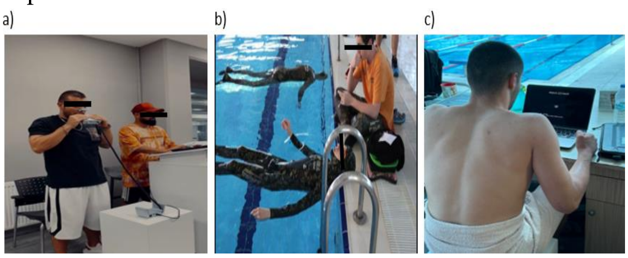

Figure 1. a) Lung Capacity Measurements, b) Breathing hold and resting position during training session, and c) Post Aquatic Hold Breathing Exercise "2-Back Test.

2.8 Cognitive Assessment

The experimental setup utilised the Psychology Experiment Building Language (PEBL), a computer-based test battery (Manci et al., 2021; Mueller & Piper, 2014; Piper et al., 2012) available at https://pebl.sourceforge.net/. Prior to the commencement of the cognitive testing, the participants were provided with detailed information regarding the procedures involved in the administration of the cognitive test. Prior to administering the primary cognitive assessments, it is imperative for the participants to adequately acquaint themselves with the testing protocols and gain a comprehensive understanding of the test prerequisites. The participants were provided with instructions indicating that the test to be administered would involve repetition, thereby mitigating the potential influence of the learning effect during the primary test. The test was conducted by the participants on a laptop in all conditions. Given the proximity of the session to a pool, a precautionary measure was implemented to prevent any potential liquid exposure in all circumstances (Figure 3c).

During the administration of the cognitive tests, the participants were instructed to assume a seated position at a distance of 70 cm from the testing materials (Brush et al., 2016). The experiments were conducted using an Apple MacBook Pro from the 2020 model lineup. The present computer possesses a 13.3-inch (diagonal) display that utilises LED backlighting and features a native resolution of 2560 x 1600, resulting in a pixel density of 227 pixels per inch.

N-Back Test

The N-back task is a widely employed assessment tool that measures various cognitive abilities, including vigilance, sustained attention, visual memory, executive functions, and short-term working memory functions. The process of maintaining and updating information involves encoding, temporary storage, and responding (Rac-Lubashevsky & Kessler, 2016). The current investigation employed a modified iteration of the n-back test, specifically the 2-back test. During the trial session, a round of testing was conducted, which included the administration of the 1-back and 2-back tests. Subsequently, the 2-back test was administered during the testing session.

During the 2-back test, a total of 120 letter sequences consisting of the letters T, G, T, V, P, V, T, and V were applied. The letters appeared on the computer screen for 500 ms and the inter-stimulus interval was 1500-2000 ms. 2-back took ~4 min. and all sessions were performed in a stable and standard protocol (Figure 2), (Leon-Dominguez et al., 2015).

In the test, participants were asked to press the designated key on the keyboard if the letter on the screen was the same as the two previous letters. The test lasted approximately four minutes. With the "2-back test", the "percentile of correct answers (%)", and "total reaction time (ms)" data were recorded on the computer.

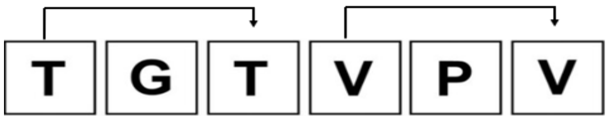

Figure 2. A Schematic Illustration of the "2-Back Test

2.9 Statistical Analysis

The JASP version 0.16.2 (JASP Team, 2018; https://jasp-stats.org/, accessed on August 31, 2023) was utilised in this study. The software application was employed for conducting statistical analysis and generating raincloud plots. The assessment of the normal distribution of the data was conducted using the Shapiro-Wilk test. Based on the outcomes of the Shapiro-Wilk test, it was determined that the variables exhibited a normal distribution. The study examined the reaction times (measured in milliseconds) and accuracy scores (measured in percentages) obtained from the N-back test. These measures were compared across three conditions: Control, Water, and Land. In cases where a difference was observed, post-hoc analyses were conducted to identify the specific source of this difference. Hence, the statistical analysis technique known as "repeated measures ANOVA" was employed.

Furthermore, a delta calculation was conducted to assess the extent to which cognitive performance varied in relation to the baseline value following land and water exercises. In this computation, the measurement data obtained from the land and water exercises were deducted from the control value. Given that the delta values did not follow a normal distribution, non-parametric tests, specifically Wilcoxon Sign Tests, were employed for conducting pairwise comparisons. Regarding the non-parametric comparisons, the rank biserial correlation on JASP provides the effect size. The rank biserial correlations "r" is rated as follows: <0.1: very small effect; ≥0.1 to ≤0.29: small effect; ≥0.3 to ≤0.49: medium effect; and ≥0.5: large effect (Fritz et al., 2012). All results were expressed as means (M) and standard deviations (SD). The significance level was set for all statistical tests at $p < 0.05$, and the effect sizes were reported as partial η2.

3. Results

3.1 Demographic and Physiologic Parameters

The study included a sample of eighteen male professional divers (age: 19.55 ± 2.89 years; body height: 172.2 ± 8.53 cm; body weight: 68.6 ± 10.26 kg). All participants had a minimum of seven years of training experience. The participants exhibited a mean forced vital capacity (FVC) of 5.95 ± 0.76 L, while their mean official personal best maximal hold breathing values were 5.26 ± 0.77 minutes. The aforementioned values represent the outcomes achieved by participants who secured positions within the top 10 rankings in national competitions.

3.2 Cognitive Tests Results

The participants' reaction times (ms) and accuracy (%) values resulting from the 2-Back test are given in Table 1.

Table 1

Participants' total reaction times (ms) and accuracy (%) results

	N	Mean Accuracy (%)	Std. Dev. ±
Co_2-Back Accuracy (%)	18	44	14.3
Wa_2-Back Accuracy (%)	18	42	13.6
La_2-Back Accuracy (%)	18	47	14.3
	N	**Reaction Time (ms)**	**Std. Dev. ±**
Co_2-Back Mean Reaction Time (ms)	18	539	95
Wa_2-Back Mean Reaction Time (ms)	18	513	78
La_2-Back Mean Reaction Time (ms)	18	556	99

Co: Control, Wa: Water, La: Land, Ms: millisecond

The analysis of the total reaction time results from the 2-N Back test revealed a notable impact of the three distinct conditions on the observed outcomes (Wilks' Lambda= 0.64, F (2,16) = 4.47, p= .029, η2: .358; Figure 3). The results of the pairwise comparison, after applying the Bonferroni correction, revealed a significant difference between the land condition (556 ± 99 ms) and the water condition (513 ± 78 ms). The findings of the study indicate that there was a significant decrease in reaction times following a breath-hold exercise session conducted on land compared to a breath-hold exercise session conducted in water (p= .021).

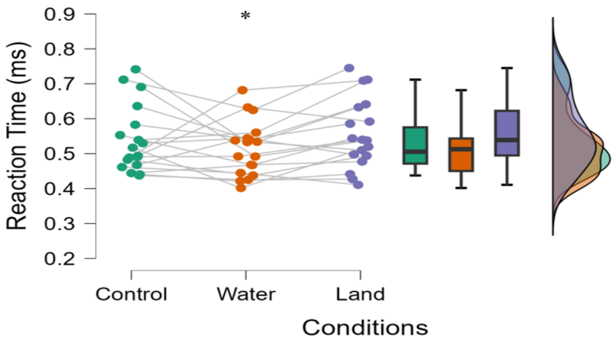

Figure 3: Participants' three different conditions 2-Back Test reaction time results. *p< .05

The comparative analysis of accuracy results across three distinct conditions revealed that the conditions did not yield a statistically significant impact on accuracy (Wilks' Lambda= 1.68, F (2,16) = 1.68, p> .05, η2: .174; Figure 4).

3.3 Delta Calculations

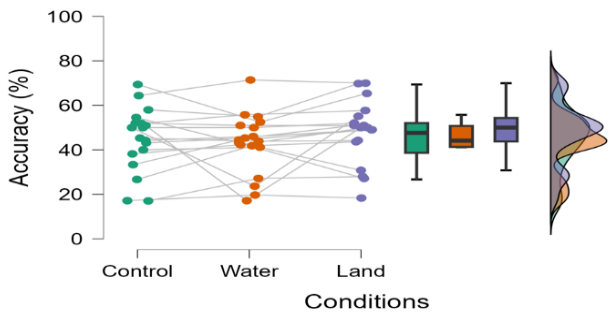

Figure 4: Participants' three different conditions 2-Back Test Accuracy results

The delta calculations were conducted to assess the changes in participants' cognitive test results across differen t conditions (water and land) in comparison to the control condition. The findings indicated that the water condition yielded significantly poorer outcomes compared to the land condition (z: -2.025, p= 0.043, r= -0.544; Figure 5).

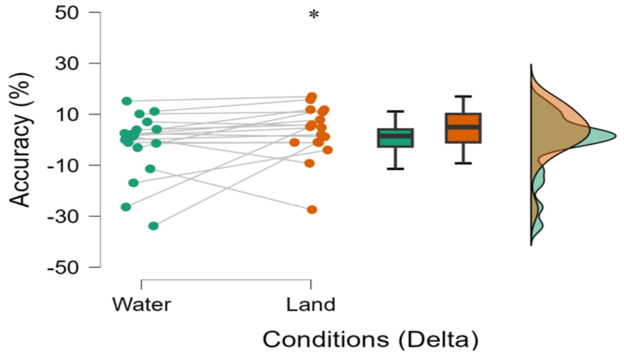

Figure 5: Participants' two different conditions 2-Back Test Accuracy Delta results. *p <0.05

The analysis of delta values pertaining to participants' reaction times revealed a noteworthy finding: reaction times were significantly quicker in the water condition compared to the land condition (z: -2.504, p= 0.010, r= -0.673; Figure 6).

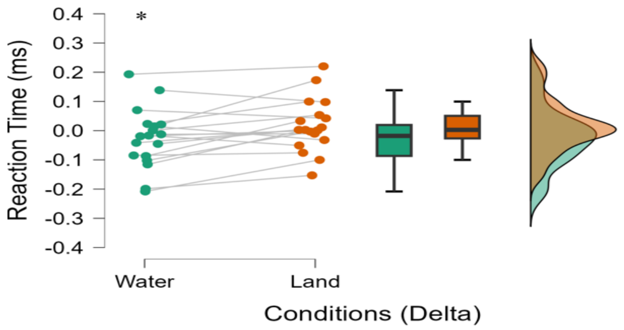

Figure 6: Participants' two different conditions 2-Back Test Reaction Time Delta results. *p< 0.05

4. Discussion

The study aimed to investigate the cognitive changes resulting from breath-holding training conducted by professional diving athletes in both water and on land conditions. The main finding of the study is the identification of impaired executive functions in the acute phase after water breath-holding training, compared to other condition (p= .029, with large effect size).

Changing the accuracy and average reaction times of correct answers on cognitive test batteries, like the 2-back task, has been found to be a good way to figure out how well executive functions are working (Lubczyk et al., 2022). Numerous studies have consistently documented positive outcomes in the realm of executive functions following exercise, particularly during the acute phase (Chang et al., 2012; Tam, 2013). The improvement observed in this context can be attributed to physiological factors, including heightened sympathetic activity (Tsuk et al., 2019), elevated levels of catecholamines (Lambourne & Tomporowski, 2010), and augmented cerebral blood flow and hemodynamic responses (Manci et al., 2023). However, the decrease in cerebral blood flow and the resulting reduction in brain oxygenation that occur during acute or chronic processes are associated with impairments in cognitive function (Ogoh, 2017).

In the context of an aquatic environment, when the head remains above the water surface, the blood tissue demonstrates a sliding motion from the peripheral regions towards the heart. This phenomenon occurs as a result of the elevation in hydrostatic pressure (Christie et al., 1990). This physiological mechanism results in an augmentation of cardiac output and a reduction in heart rate, thereby enhancing the overall efficiency of bodily functions (Wilcock et al., 2006). According to available reports, it has been observed that cerebral blood flow tends to increase under specified conditions. Additionally, exercises conducted with the head positioned outside of the water have been found to enhance cognitive function (Sato et al., 2015).

Within the existing body of literature, there exists a limited number of studies that have examined the cognitive functions of individuals who engage in diving activities utilising the Self-Contained Underwater Breathing Apparatus (SCUBA). However, we were unable to locate any research that specifically examined the cognitive function of breath-hold divers in authentic environmental settings. In a specific investigation, it has been ascertained that engaging in repetitive SCUBA dives, even while strictly following decompression tables, can lead to the formation of microlesions in the myelin sheath. The presence of microlesions has the capacity to interfere with neuronal function in the central nervous system.

Furthermore, it is worth noting that these microlesions have the potential to play a role in the development of enduring alterations in the white matter of the brain, which can ultimately result in cognitive decline (Coco et al., 2019). According to a separate investigation, it has been documented that individual who engaged in a 20-meter SCUBA dive during the acute phase exhibited deficiencies in executive functions and reaction times. The impairments observed in individuals following a dive have been linked to elevated levels of cortisol, resulting in cognitive decline (Pourhashemi et al., 2016).

In the realm of breath-hold diving, it has been established that following breath-hold training, divers experience a gradual decline in the partial pressure of oxygen, resulting in a subsequent decrease in oxygen saturation (Bosco et al., 2020). Despite the extensive training experience and adaptation to hypoxic conditions exhibited by the divers in the study, their cognitive executive functions were significantly impaired as a result of this training load. Of particular significance is the notable augmentation in response times and the concomitant reduction in the quantity of accurate responses.

The aforementioned impact has notable implications for essential cognitive processes such as perception, decision-making, and working memory capacity in comparison to the control condition. The potential mechanisms thought to contribute to this outcome encompass the activation of the diving reflex, which redirects oxygen towards essential organs upon contact with water and breath-holding, as well as the brain's exposure to more limited oxygen conditions resulting from prolonged dive durations. Another corroborating discovery is the notable enhancement in executive functions subsequent to the implementation of the identical breath-hold protocol on solid ground, as opposed to the aquatic environment, where the absence of "impulsivity" was noted.

Limitations

The study has certain limitations that should be acknowledged. The participant number is low due to the specific population of male professional free divers and the potential impact of the defined inclusion criteria, especially training age, on the research outcomes. Nevertheless, we believe that the results provide evidence for the relevant literature.

5. Conclusion

The findings of this study suggest that the practise of breath-holding exercise training in surface water conditions, when implemented among divers, may have a negative impact on executive functions. Moreover, it has been noted that the utilisation of identical breath-holding exercises in terrestrial environments yields a moderate enhancement of executive functions. It is anticipated that the findings of this study will make a valuable contribution to the development of training protocols for free diving athletes and coaches, while also enhancing our understanding of the implications for diver well-being.

It is advisable for coaches and athletes in the domain to refrain from engaging in demanding cognitive activities (such as deep diving, extended breath holding, or driving after training) following breath-holding exercises of a similar nature. In forthcoming research endeavours, it is imperative to undertake an examination of the potential impacts stemming from various respiratory patterns, including hyperventilation and deep diving, within distinct training regimens that cater to sizable cohorts of participants.

Author Contributions

Writing—original draft preparation, G.T., E.M., and E.G., writing—review and editing, all authors have read and approved the published version of the manuscript.

Informed Consent Statement

The Ethics Committee of Trakya University approved all procedures and the experimental design (TUTF-GOBAEK 2023/248). The study protocol is in accordance with the latest version of the Declaration of Helsinki (2004). All participants were informed about the aims and risks of the study and provided written informed consent to participate.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments

We would like to thank all the participants in the study.

Conflicts of Interest

The authors declare no conflict of interest.

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