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ORIGINAL RESEARCH

Comparison of resting-state alpha frequency and prefrontal cortex activation patterns between elite retired amateur boxers and healthy individuals: an fNIRS and EEG study

Muhammed Sıddık Çemç[1,*], Murat Kaldırımcı[2]

[1]Department of Physical Education and Sports, Boğaziçi University, 34342 Istanbul, Türkiye
[2]Department of Coaching Education, Faculty of Sport Sciences, Atatürk University, 25240 Erzurum, Türkiye

***Correspondence**
mscemc@gmail.com
(Muhammed Sıddık Çemç)

Abstract

Background: The aim of this research is to investigate resting-state alpha frequency (α) of spectral powers (μV^2) and cerebral activation changes in the prefrontal cortex (PFC) during the Stroop test in elite amateur boxers. The findings are compared with healthy individuals to evaluate the presence of chronic traumatic brain injury (CTBI). **Methods**: Electroencephalography (EEG) measurements were performed in the resting state with eyes open and closed. Functional Near Infrared Spectroscopy (fNIRS) recordings were taken from the PFC during the presentation of Stroop test stimuli to the participant in block form. **Results**: No significant difference was observed between the groups' alpha frequency (α) of spectral powers (μV^2). During the Stroop test congruent task, boxers showed significantly lower activation levels over the right dorsomedial prefrontal cortex (dmPFC) and during the incongruent task over the left dorsomedial prefrontal cortex (dmPFC) compared to the healthy control group. In addition, when the general activation during the Stroop test was examined, boxers also recorded a significantly lower activation level over the left dorsolateral prefrontal cortex (dlPFC)/ventrolateral prefrontal cortex (vlPFC)/ventromedial prefrontal cortex (vmPFC)/orbitofrontal cortex (OFC) compared to the healthy control group. No significant difference was detected regarding the Stroop test results. In conclusion, no difference was observed between boxers and healthy individuals regarding the alpha frequency of (α) spectral powers (μV^2). However, during the Stroop test, boxers displayed significantly lower cerebral activation over the left and right dmPFC and left dlPFC/vlPFC/vmPFC/OFC compared to healthy individuals. **Conclusions**: This research has demonstrated that the brain activity of retired elite amateur boxers, particularly the activation levels in the PFC while the Stroop test is conducted, is lower compared to healthy individuals. The neurological health of athletes participating in contact sports such as boxing should be closely monitored, and larger-scale, long-term studies should be conducted to investigate the effects more thoroughly.

Keywords
Boxing; Electrophysiology; Neurobiology; Neuropsychology

1. Introduction

Boxing consists of participants enduring repeated blunt force trauma to the head and body [1]. It is one of the sports with the highest risk of injury [2]. Boxers are at risk of acute and long-term neurological damage since the head is the primary target for opponents [3]. Chronic traumatic brain injury (CTBI) or chronic traumatic encephalopathy (CTE) is considered by some authorities as the most serious health issue in modern boxing [4]. CTBI is a neurodegenerative disease that develops as a result of repeated head impacts and progressively worsens over time. The characteristic symptoms of CTBI include memory loss, cognitive impairments, behavioral changes and a decline in motor functions. In addition, depression, aggressive behaviors and the eventual development of dementia are also commonly observed symptoms [5]. This condition has been given several names in medical and non-medical literature, including "dementia pugilistica" or "punch drunk" syndrome [6]. Dementia pugilistica is a neurodegenerative disease typically observed in boxers caused by repeated head trauma. This condition is also known as CTBI and results from accumulated brain injuries over time. The most common symptom of dementia pugilistica is dementia, and the disease is characterized by symptoms such as impaired motor coordination, difficulty in speech (dysarthria), cognitive decline, memory loss and personality changes [7]. CTE is believed to represent the cumulative long-term neurological consequences of repeated severe blows to the head [4, 8]. CTE is more prevalent in professional boxers than in amateur ones, but it has also been identified in other sports, such as American football, ice hockey, rugby, horse racing and soccer [9, 10].

Between the year 1732 and November 2007, a total of 1465 deaths worldwide have been recorded due to boxing. Approximately 70% of these fatalities have occurred in professional boxers. While the number of deaths has significantly decreased since the 1960s, there is still an average of 77 fatalities every decade [11]. The majority of these deaths occur due to the progression or not being diagnosed with cognitive disorders or severe concussions and injuries sustained during matches. There is substantial evidence indicating that these concussions alone can result in cognitive disorders [12, 13]. Additionally, recent research indicates that dementia is significantly more prevalent among professional boxers compared to amateurs, with a prevalence rate of approximately 20% [14].

Recent research has focused on examining CTBI caused by sports activities and its clinical findings in greater detail [15–17]. It has been reported that many boxers experience memory problems not only in the early stages following matches but also in their daily lives long after [18]. Clinical findings related to motor, cognitive or behavioral disorders have been observed to manifest in some cases after a boxer's career ends, with neurological signs becoming more pronounced in retired boxers over the age of 50 [16]. Boxing is considered a sport that seriously damages the central nervous system, whether acutely or chronically. Moreover, this damage is not accidental but is intentionally inflicted as part of the sport. In light of this, some authors advocate for the banning of boxing [19–23]. However, there are also publications suggesting that banning the sport is not a rational solution and that legal, medical, and educational measures could offer a more reasonable approach to addressing the issue [24–26].

The traumatic encephalopathy that boxers encounter, colloquially known as "punch drunkenness" [27], stems from the cumulative effects of repetitive brain trauma experienced over a boxer's career [28]. In some cases, this condition results in permanent brain damage [29], and sometimes it can initiate a degenerative process that continues even after an active boxing career has been abandoned [30, 31]. Consequently, researchers have turned to investigating the electrical activity of the brain to detect encephalopathy at early stages [32].

The purpose of this study is to investigate the alpha frequency (α) of spectral powers (μV^2) at rest in elite retired amateur boxers, to assess the changes in cerebral activation that occur in the PFC during the application of the Stroop test, and to evaluate the resultant data concerning healthy individuals, specifically in terms of CTBI.

2. Materials and methods

Measurements for the current research were taken according to the present Helsinki Declaration at the Neuropsychology Laboratory of the Atatürk University.

2.1 Participants

The study was carried out with right-handed participants who received undergraduate-level education. Ten male boxers, 28 ± 3.16 years as their average age, having actively boxed for an average of 13.1 ± 2.46 years and on average, 4.3 ± 1.33 years having elapsed since quitting the sport, were included in the study. In addition, ten males with no pathologic background and were 25.5 ± 4.08 years old on average were involved as the control group. The control group had no previous engagement in any combat sports and was recruited in June and July 2022.

Inclusion criteria for the participants ensured that they were healthy, with no chronic or acute medical conditions, psychological disorders, psychosis or neurological disorders. Participants were also required to be free of any neurodegenerative diseases that could increase intracranial pressure or impair cerebral blood flow, as well as conditions such as epilepsy that could lead to abnormal neuronal discharge activity in the brain. Furthermore, they had not used any medications or stimulants that could affect central nervous system function or cognitive performance, and they possessed normal vision and normal color vision. Participants were also asked to refrain from consuming alcohol, tobacco or caffeine for 24 hours prior to the measurements and tests.

2.2 Study design

Participants were informed about the measurement devices and the test. The tests were implemented in a 21 °C degree and 15 Db setting with optimal humidity and isolated from electromagnetic fields. The temperature and humidity of the test environment were continuously monitored and recorded using a Testo 622 digital thermohygrometer (Titisee-Neustadt, Germany). This device was checked at regular intervals every 15 minutes throughout the testing process to ensure a stable temperature of 21 °C and optimal humidity levels. When deviations in temperature or humidity were detected, adjustments were made using the Daikin FTXF25E air conditioner (Osaka, Japan) and Levoit LV600HH humidifier (Anaheim, CA, USA). Tests and measurements were performed on all participants in the same environment, ensuring they were in comfortable clothing and without the presence of hunger or fatigue. The time allotted for the test was sufficient and equally set for everyone. The data collection process was completed over 2 days and in 2 sessions for each participant. Additionally, considering the biological clock, participants were ensured to attend the tests and measurements at noon.

2.3 Measures

2.3.1 Edinburgh inventory hand preference survey

In order to determine the hand preferences of the participants, the "Edinburgh Inventory Hand Preference Survey" [33] was filled out by the participants. They were asked to answer the questions contained in the survey based on their hand preferences. The given responses were evaluated according to the Geschwind score. The scores given according to hand preferences were totaled. Consequently, the levels of being left-handed, ambidextrous and right-handed were determined using this method.

2.3.2 EEG measurements

EEG is a method for recording variations in the brain's electrical potentials [34]. An EEG provides a record of the occurring electrical potential oscillations. These are recorded by amplifying voltage variations that change over time between electrodes positioned on the scalp [35]. EEG provides a non-invasive neuro-electrophysiological method that effectively assesses neurological function by detecting electrophysiological information associated with cognitive processing, with high-precision temporal resolution at the millisecond level [36]. EEG is a valuable tool in traumatic brain injury (TBI) research. Due to its ability to directly measure electrical activity in the brain, EEG is widely used to detect the severity and effects of brain injury [37–39].

Participants provided their informed consent by signing the "Informed Consent Form", approved by the Institutional Ethics Committee of the Faculty of Sport Sciences at Atatürk University, prior to the commencement of the EEG recording session. EEG signals were recorded using the ActiChamp device (Brain Product). During recording, electrodes were designed according to the international 10/20 system for data collection, and all electrode impedance values remained below 5 KΩ throughout the data acquisition process. The "Fz" channel was designated as the reference electrode. The sampling frequency was set at 250 Hz.

Measurements were conducted with participants seated comfortably in a chair, approximately 1.5 meters away from a 28-inch Liquid Crystal Display (LCD) monitor placed at eye level. Prior to initiating measurements, participants were provided with the necessary information. The EEG cap was applied to participants' scalps with the assistance of conductive gel. During the measurement, participants were instructed through the LCD monitor to perform both "Eyes Open" and "Eyes Closed" conditions. EEG recordings were obtained for 3 minutes with eyes open and 3 minutes with eyes closed.

After the recording, an average was calculated for each participant and the alpha (8–13 Hz) frequency of spectral powers was measured and checked. The measurements were completed by analyzing the values obtained from electrode placements over the following channels: Fp1, Fp2 in the frontopolar region; F3, F4 in the frontal region; C3, Cz, C4 in the central region; P3, Pz, P4 in the parietal region and O1, Oz, O2 in the occipital region.

2.3.3 fNIRS measurements

fNIRS is also a non-invasive method intended to provide imaging and functional measurement techniques for brain biophysics, psychophysiology and the clinical field [40, 41]. Data can be gathered from the prefrontal area using the fNIRS imaging technique within the infrared light range. Infrared light is used to detect deoxyhemoglobin (HHb) and oxyhemoglobin (HbO_2) concentrations [42]. The fNIRS method can currently be widely used to investigate neuropsychological functions such as vision, executive functions, motor activity, somatosensory activity, attention, memory and language [43]. fNIRS is presently employed to inquire about neural information processes regarding to neurological disorders like minor cognitive damage [44, 45], Alzheimer's [46], Parkinson's [47], stroke [48], traumatic brain injury (TBI) [49] and also psychiatric conditions like schizophrenia [50] and anxiety [51].

During the presentation of stimuli, fNIRS technology was employed to measure changes in hemoglobin concentration over the PFC of the participants. fNIRS data was collected by putting a cap/headgear on the attendants' heads, using the NIRSport2 gadget (NIRx Medizintechnik GmbH, Berlin, Germany) with 16 optodes (eight sources and eight detectors). The optodes were placed on the PFC in line with the experimental objectives [52], and measurements were recorded in the 760–850 nm range using continuous wave (CW) methodology. The color-word Stroop test (CWST) compatible stimuli, both congruent and incongruent, were shown to attendants in a block design through the Psychtoolbox for MATLAB 2018a program.

Differences in oxygenated HbO_2 in the cerebral cortex of attendants were noted while the stimuli were shown. The analysis was set out to discover the dissimilarities among the neurophysiological conditions while stimuli were shown (quantity of HbO_2) and the baseline state by subtracting the amount of baseline HbO_2.

Posterior to putting the optodes on attendants' heads while they are sitting, measurements were noted the Stroop test was conducted with a computer. Placing the caps and optodes, and the recordings took around a quarter of an hour. Behavioral data were combined with measurements from the fNIRS device for further analysis.

The fNIRS data was handled with a Principal Component Analysis (PCA) filter applied through scripts created in MATLAB 9.0 software (MathWorks, Natick, MA, USA), and the data collected between 5–25 seconds was examined under the Contrast-to-Noise Ratio (CNR) method. The CNR matrix operation includes determining the baseline average of 60 seconds at the start and finish of the task, subtracting the highest HbO_2 value formed within the 5 to 25-second interval, and consequently ending the procedure by dividing the end value by the HbO_2 standard deviation that occurred over the baseline.

Quantities of HbO_2 measured in the PFC of the brain were recorded at a frequency rate of 10.1725 Hz. After calculating HbO_2 quantities, a Butterworth low-pass filter with a cutoff frequency of 0.25 Hz was applied to discard baseline deviations and clear away fluctuations caused by heart rate, respiration, *etc*.

2.3.4 Stroop test

Neuropsychological tests have been observed to be sensitive in detecting cognitive impairments stemming from contact and collision sports [53–55]. To evaluate selective attention in individuals with TBI, the Stroop test was created by J.R. Stroop in 1935 [56]. There is a consensus regarding the use of the Stroop test for assessing functions of the frontal lobe [57, 58]. In 1886, James McKeen Cattell demonstrated that stating the names of colors and various objects took longer than reading the words that denote them. J.R. Stroop revealed in 1935 that this scenario caused a color-word disruptive effect. Stroop designed this test targeting cognitive control, consisting of three parts.

In the first part, participants are shown color names and asked to read them aloud quickly. In the second part, participants are shown colored dots and asked to vocalize the colors quickly. In the third part, a color name is shown in writing, but the color of the text differs from the color represented by the word. For instance, the word "blue" might be displayed in red. Here, several color names are shown consecutively, and the participant is asked to read the words out loud in quick succession. In this instance, the correct reading would be "blue". It is observed that participants struggle with this task, often verbalizing the color of the word rather than the color name written or hesitating before speaking. It has been found that the time taken to state the color is longer when the meaning of the word and the color of the ink is different (the word "blue" written in red) compared to when they match (the word "blue" written in blue). This delay is termed the Stroop interference effect and occurs as the participant attempts to read the written color while also stating the color of the ink [59].

The Stroop test includes two sections: congruent and incongruent [60]. In the congruent section, the color shown at the beginning was projected in line with the text (*e.g.*, The word "RED" shown against a red background, "GREEN" shown against a green background or "BLUE" shown against a blue background), and attendants were requested to match it with the possibilities provided below. In the incongruent task, the colors and text were mismatched, and participants were instructed to identify the color displayed above by selecting the corresponding text from the two options provided below. Everything was written in Turkish. A 28-inch LCD screen placed at eye level and approximately 1.5 meters away from the participants was employed to show the stimuli.

Participants were asked to give answers by pushing the "←" and "→" directional buttons with their right index fingers. Prior to starting the Stroop test, the content of the test was presented, and a trial (2 minutes) was completed by the attendants. After this, the fNIRS cap was put on the attendants' heads, and the required calibration steps were completed.

The Stroop task was conducted in six sections, made up of three blocks, each with 16 congruent and 16 incongruent tasks, with 30-second breaks in between. A one-minute baseline was measured at the start and end of the task. Reaction time and error rate were measured (Fig. 1). The stimulus remained on the screen until a response was made or for 2000 milliseconds. Stimuli were presented at intervals of 1000 milliseconds. Responses given within 200 to 2000 milliseconds after the stimulus is shown are considered correct. Responses not within the time range (200–2000 milliseconds) or the wrong color button press were deemed incorrect. After all attendants' measurements were finished, analyses were conducted.

2.4 Statistical analysis

Standard statistical methods were utilized for the computation of means and standard deviations in data analysis. The sample size for this study was determined through a priori power analysis conducted using G*Power 3.1.9.7 (Heinrich Heine University, Düsseldorf, NRW, Germany), based on expected differences in PFC activation levels measured by fNIRS during the Stroop test. The analysis indicated the need for 20 participants, assuming a medium effect size ($f = 0.25$), a Type I error rate (α-level) of 0.05, a power ($1 - \beta$) of 0.80, two groups, six repeated measurements, a correlation among repeated measures of 0.5 and a nonsphericity correction (ϵ) of 1. Accordingly, 20 participants (10 per group) were included in the study, fully meeting the calculated requirements. A *post-hoc* power analysis was also conducted using the same software and parameters to evaluate the achieved statistical power, which was calculated as 0.841. This confirms that the study had sufficient power to detect significant effects within the specified parameters. The alpha frequency of spectral power values and Stroop test data were assessed using the IBM SPSS Statistics 22.0 package (IBM Corp., Armonk, NY, USA). To evaluate the difference between groups in the alpha frequency of spectral powers and Stroop test data, the Mann-Whitney U test was applied. The activation levels on the PFC during the Stroop test were evaluated using the Repeated Measures Analysis of Variance (ANOVA) test in the JASP 0.19 program (University of Amsterdam, Nieuwe Achtergracth, Amsterdam, Netherlands). Rank-Biserial Correlation (r_{rb}) and Cohen's d were used as effect size indices for the obtained data. The significance level for the analyses was accepted as $p < 0.05$.

3. Results

No significant differences were observed in the alpha frequency of spectral power values obtained from the frontopolar, frontal, central, parietal and occipital regions during the eyes-open resting state between the groups. For detailed statistical values, refer to Table 1.

No significant differences were found in the alpha frequency of spectral power values obtained from the frontopolar, frontal, central, parietal and occipital regions during the eyes-closed resting state between the groups. Detailed results are presented in Table 2.

The cerebral activation level formed in the healthy controls while the general Stroop test was implemented (Fig. 2) was significantly higher in the right dmPFC (channel 3; $p = 0.021$, Cohen's $d = 0.908$, $1 - \beta = 0.652$ and channel 8; $p = 0.02$, Cohen's $d = 0.886$, $1 - \beta = 0.631$), left dmPFC (channel 6; $p = 0.009$, Cohen's $d = 0.968$, $1 - \beta = 0.708$), left dlPFC/vlPFC/vmPFC/OFC (channel 20; $p = 0.004$, Cohen's $d = 0.978$, $1 - \beta = 0.716$ and channel 22; $p = 0.026$, Cohen's $d = 0.915$, $1 - \beta = 0.660$) regions compared to boxers.

The cerebral activation level formed in the healthy control group at the time of the Stroop test Congruent Stimuli (Fig. 3) was significantly higher in the right dmPFC (channel 3; $p = 0.021$, Cohen's $d = 0.908$, $1 - \beta = 0.652$) region compared to boxers.

The cerebral activation level formed in the healthy control group at the time of the Stroop test Incongruent Stimuli (Fig. 4) was significantly higher in the left dmPFC (channel 6; $p = 0.009$, Cohen's $d = 0.968$, $1 - \beta = 0.708$) region compared to boxers.

Table 3 displays the score differences that occurred between groups of participants based on their performance in the Stroop test. Statistical analysis shows that regarding error rates in

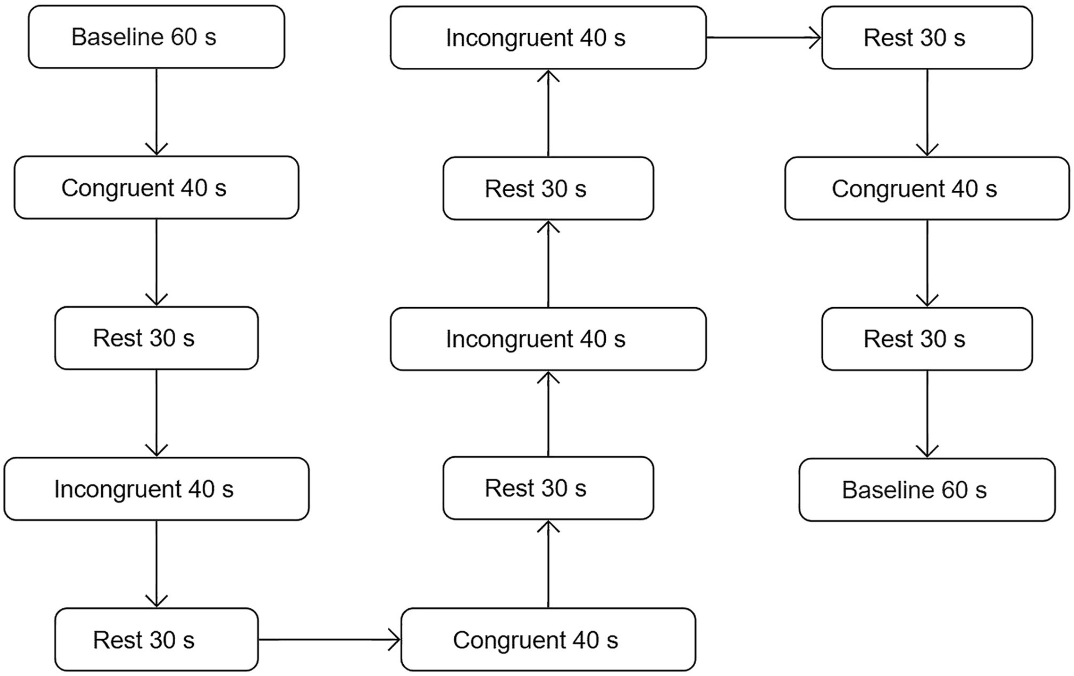


FIGURE 1. The order of the Stroop test paradigm modified to align with fNIRS measurement protocols.

TABLE 1. Statistical comparison of the participants' intergroup resting, eyes-open alpha frequency of spectral power values.

Electrode Placements		Boxer n = 10	Control n = 10	u	z	p	r_{rb}	$1 - \beta$
Region	Channel	Mean ± SD	Mean ± SD					
Frontopolar								
	Fp1	1.468 ± 2.176	2.559 ± 3.448	44.000	−0.454	0.650	0.120	0.057
	Fp2	6.260 ± 4.436	6.459 ± 3.993	47.000	−0.227	0.821	−0.060	0.051
Frontal								
	F3	2.872 ± 1.801	2.338 ± 1.956	36.000	−1.058	0.290	0.280	0.091
	F4	6.305 ± 4.012	8.412 ± 5.314	36.000	−1.058	0.290	−0.280	0.091
Central								
	C3	3.598 ± 2.081	3.355 ± 2.535	44.000	−0.454	0.650	0.120	0.057
	Cz	8.033 ± 5.313	14.450 ± 10.897	32.000	−1.361	0.174	−0.360	0.118
	C4	8.401 ± 6.931	12.240 ± 10.568	44.000	−0.454	0.650	−0.120	0.057
Parietal								
	P3	5.563 ± 4.327	5.800 ± 4.268	49.000	−0.076	0.940	0.020	0.502
	Pz	5.817 ± 3.894	6.544 ± 4.713	47.000	−0.227	0.821	−0.060	0.051
	P4	8.274 ± 5.951	11.526 ± 9.168	44.000	−0.454	0.650	−0.120	0.574
Occipital								
	O1	5.016 ± 4.041	4.394 ± 3.261	43.000	−0.529	0.597	0.140	0.060
	Oz	6.375 ± 4.981	5.196 ± 3.991	41.000	−0.680	0.496	0.180	0.066
	O2	6.604 ± 4.481	9.175 ± 7.291	42.500	−0.567	0.571	−0.150	0.061

u: The test statistics obtained from comparing the ordinal data between two independent groups.
z: The standardized test statistic that assesses the normality of the U value's distribution.
$p < 0.05$: Indicates statistical significance, with data presented as mean ± standard deviation in units of spectral powers (μV^2).
r_{rb}: Used to evaluate the effect size after the Mann-Whitney U test.
$1 - \beta$: Power, representing the probability that the test will correctly detect a true difference.

TABLE 2. Statistical comparison of the participants' intergroup resting, eyes-closed alpha frequency of spectral power values.

Electrode Placements		Boxer n = 10	Control n = 10	u	z	p	r_{rb}	$1-\beta$
Region	Channel	Mean ± SD	Mean ± SD					
Frontopolar								
	Fp1	1.786 ± 2.523	2.446 ± 4.200	40.500	−0.718	0.473	0.190	0.068
	Fp2	14.818 ± 12.338	27.758 ± 20.062	30.000	−1.512	0.131	−0.400	0.135
Frontal								
	F3	2.260 ± 1.341	2.499 ± 2.610	42.500	−0.567	0.571	0.150	0.061
	F4	17.171 ± 13.647	30.300 ± 24.952	33.000	−1.285	0.199	−0.340	0.111
Central								
	C3	3.285 ± 2.425	3.415 ± 2.831	47.500	−0.189	0.850	0.050	0.051
	Cz	19.982 ± 18.830	28.468 ± 27.624	41.000	−0.680	0.496	−0.180	0.066
	C4	19.951 ± 23.456	24.015 ± 26.242	42.000	−0.605	0.545	−0.160	0.063
Parietal								
	P3	6.658 ± 7.145	6.028 ± 4.210	46.500	−0.265	0.791	−0.070	0.052
	Pz	6.459 ± 5.531	7.763 ± 5.128	41.000	−0.680	0.496	−0.180	0.066
	P4	12.303 ± 11.850	14.194 ± 14.690	47.500	−0.189	0.850	−0.050	0.051
Occipital								
	O1	5.707 ± 4.999	7.296 ± 4.583	36.000	−1.058	0.290	−0.280	0.091
	Oz	10.540 ± 9.178	12.296 ± 11.247	41.000	−0.680	0.496	−0.180	0.066
	O2	11.644 ± 10.164	17.111 ± 9.482	28.000	−1.663	0.096	−0.440	0.153

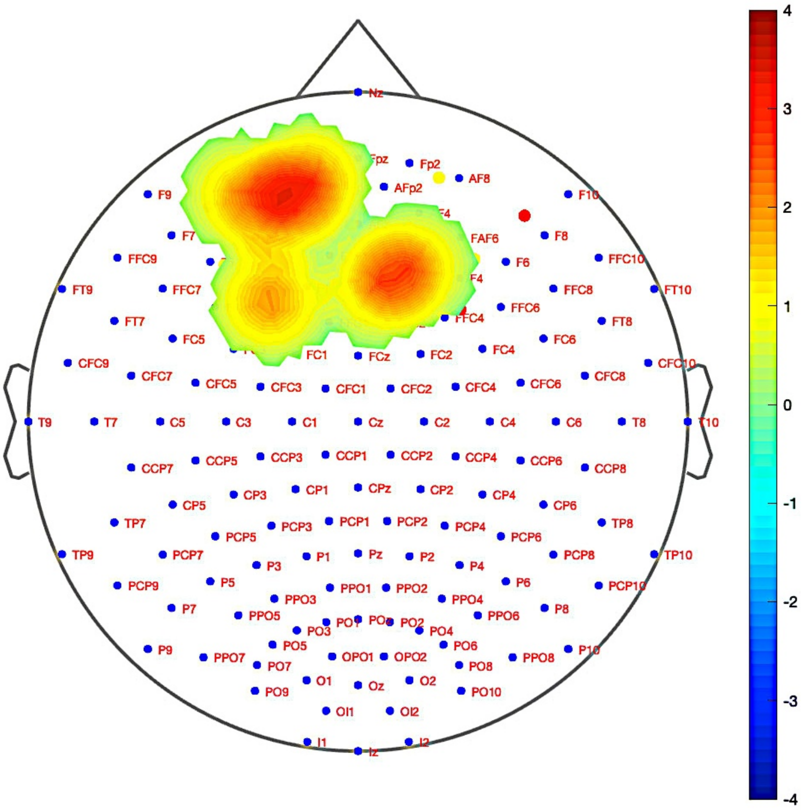
u: The test statistics obtained from comparing the ordinal data between two independent groups.
z: The standardized test statistic that assesses the normality of the U value's distribution.
$p < 0.05$: Indicates statistical significance, with data presented as mean ± standard deviation in units of spectral powers (μV^2).
r_{rb}: Used to evaluate the effect size after the Mann-Whitney U test.
$1-\beta$: Power, representing the probability that the test will correctly detect a true difference.

the congruent test, boxers had an incorrect answer level of 0.625 ± 1.406, while controls had 1.250 ± 1.757. Boxers showed a lower error rate. Nonetheless, this dissimilarity is not significant on a statistical level (u = 40.000, z = −0.936, p = 0.349, r_{rb} = −0.200, $1-\beta$ = 0.070). Examining the response period in the congruent task, boxers had a time of 1.0599 ± 0.123 seconds, while the healthy group had 1.0523 ± 0.198 seconds. The control participants presented a decreased response period than the boxers. But again not a statistically significant one (u = 47.000, z = −0.227, p = 0.821, r_{rb} = 0.060, $1-\beta$ = 0.051). Regarding error rates in the incongruent task, boxers had an error level of 1.041 ± 2.643, while healthy individuals had 2.917 ± 4.073. Boxers showed a lower error rate than healthy individuals but not a significant one on a statistical level (u = 34.500, z = −1.376, p = 0.169, r_{rb} = −0.310, $1-\beta$ = 0.100). Examining the reaction times in the incongruent task, boxers had 1.2355 ± 0.183 seconds, while healthy individuals had 1.1834 ± 0.194 seconds. The healthy individuals exhibited a lesser response period than the boxers but not a significant one on a statistical level (u = 36.000, z = −1.058, p = 0.290, r_{rb} = 0.280, $1-\beta$ = 0.091).

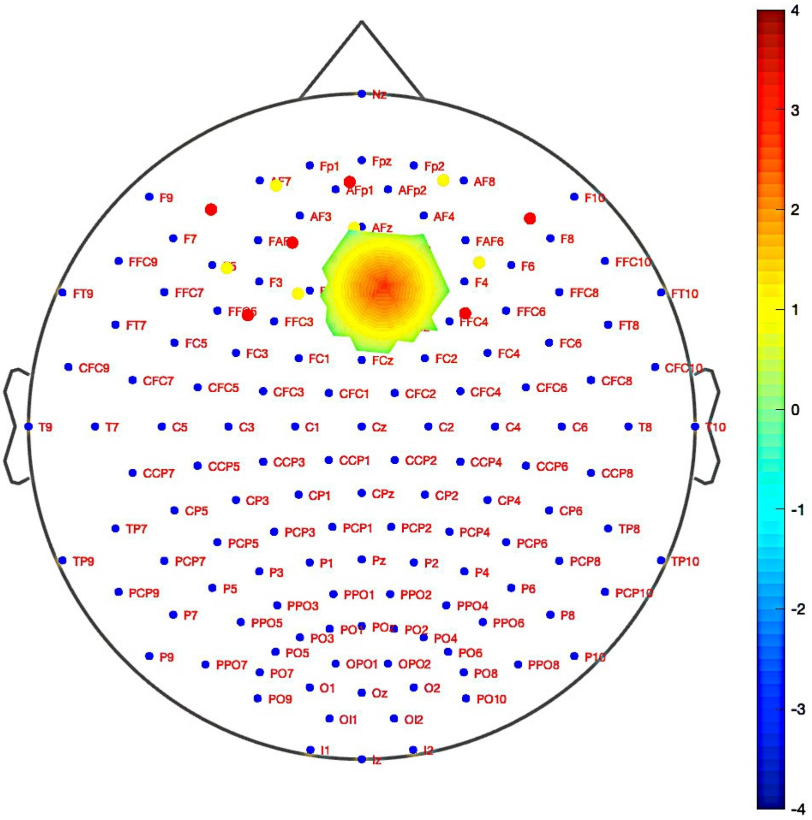
4. Discussion

When the alpha frequency of spectral power (μV^2) values in resting state with eyes open and closed were examined, no statistically significant difference was observed between the two groups in terms of spectral powers (μV^2) in channels Fp1, Fp2 in the frontopolar region; F3, F4 in the frontal region; C3, Cz, C4 in the central region; P3, Pz, P4 in the parietal region; and O1, Oz, O2 in the occipital region.

In their study, Rodriguez *et al.* [61] found no significant difference in regional cerebral blood flow between amateur boxers, judo athletes, and the control group. However, in professional boxers, this was significantly lower in the frontocentral region. EEG levels were observed to be normal in all judo athletes and amateur boxers, but 3 professional boxers exhibited abnormal conditions. Haglund and Persson [62], in a study to investigate potential brain damage related to amateur boxing in Sweden, included 47 former amateur boxers and two separate control groups consisting of 25 footballers and 25 athletes in the same age range. No EEG abnormalities were detected between the groups. No serious chronic brain damage symptoms were found among amateur boxers, footballers and athletes. Ross *et al.* [63] examined 40 former boxers for 3 years to determine the neurological effects of boxing. A



F I G U R E 2. **Topographic images of the PFC showing activation during the general Stroop test, derived from changes in activation levels across participant groups using the CNR method.**



F I G U R E 3. **Topographic images of the PFC showing activation patterns in response to congruent stimuli, derived from changes in activation levels across participant groups using the CNR method.**

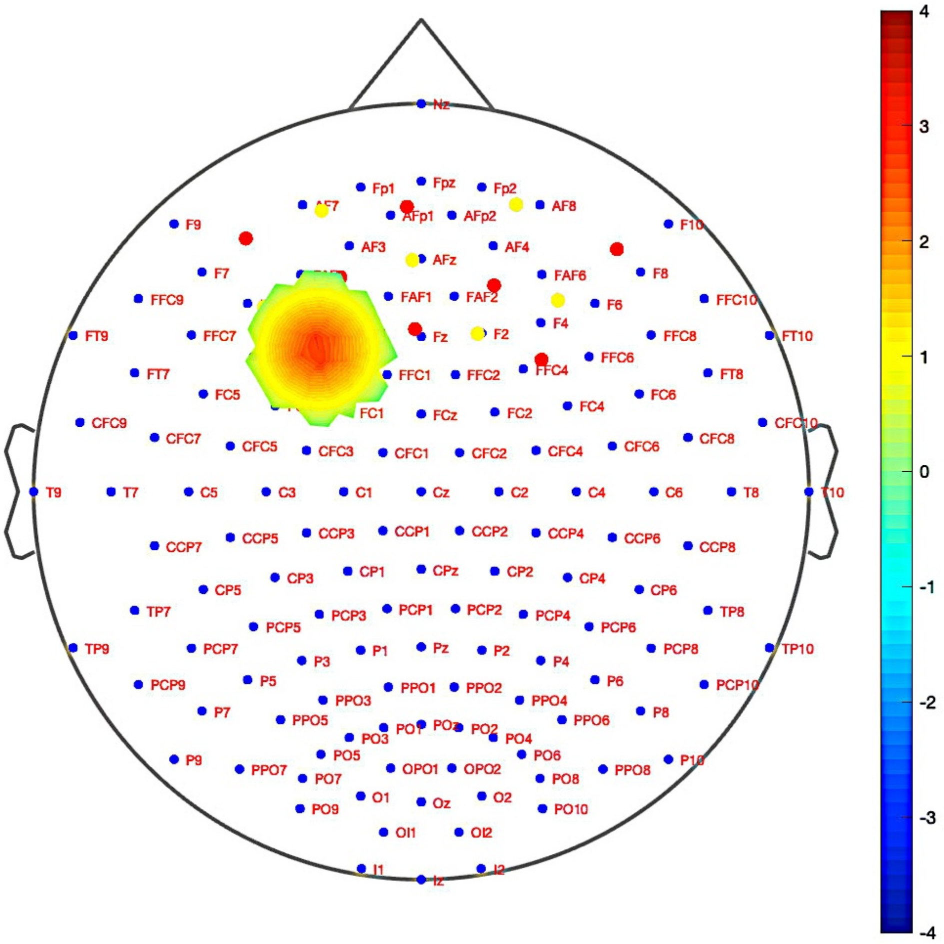


FIGURE 4. Topographic images of the PFC showing activation patterns in response to incongruent stimuli, derived from changes in activation levels across participant groups using the CNR method.

TABLE 3. The statistical comparison of inter-group differences in Stroop test scores among participants.

Test	Group	n	Mean ± SD	u	z	p	r_{rb}	$1-\beta$
Congruent Error Rate								
	Boxer	10	0.625 ± 1.406	40.000	−0.936	0.349	−0.200	0.070
	Control	10	1.250 ± 1.757					
Congruent Reaction Time								
	Boxer	10	1.059 ± 0.123	47.000	−0.227	0.821	0.060	0.051
	Control	10	1.052 ± 0.198					
Incongruent Error Rate								
	Boxer	10	1.041 ± 2.643	34.500	−1.376	0.169	−0.310	0.100
	Control	10	2.917 ± 4.073					
Incongruent Reaction Time								
	Boxer	10	1.235 ± 0.183	36.000	−1.058	0.290	0.28	0.091
	Control	10	1.183 ± 0.194					

u: The test statistics obtained from comparing the ordinal data between two independent groups.
z: The standardized test statistic that assesses the normality of the U value's distribution.
$p < 0.05$: Indicates statistical significance, with data presented as mean ± standard deviation for error rate (count) and reaction time (seconds).
r_{rb}: Used to evaluate the effect size after the Mann-Whitney U test.
$1-\beta$: Power, representing the probability that the test will correctly detect a true difference.

full neurological evaluation, including EEG, was performed on 24 of the participants. Electroencephalographic abnormalities were found to be significantly associated with the number of matches the boxers had, but there was no significant correlation between knockouts, technical knockouts and symptoms. Hence, they reported that their study supports many other studies in the literature showing that boxing is harmful to the human brain. Larsson and Melin [64] found irregular and slow EEG activity in 13% of amateur boxers from the EEG records taken 15 to 30 minutes after the match. This rate rises to 30% if the boxers receive a knockout blow during the match. Kaplan and Powder [65] reported the EEG findings of over 1000 professional boxers. No significant difference was found in the EEGs recorded after the match. However, it was observed that the EEG records of unsuccessful boxers were more irregular than successful boxers. Pampus and Grote [66] examined 250 active and 17 retired boxers by taking EEG records. They found a relationship between the frequency of abnormal EEGs and the number of matches. The resting EEG after three or more matches per week was determined to be abnormal in 42% of the cases. Especially in young people, these abnormalities resolved slowly, and it was reported that boxers should be kept away from boxing until their EEG records returned to normal. Critchley [30] stated that EEG changes are widely seen in boxers and that more abnormal records were found in those suffering from punch drunkenness. He also suggested that EEG could be used to detect and screen boxers in the early stages of encephalopathy.

Alpha peak frequency is the frequency with the highest power value in the alpha oscillation range [67]. The alpha peak frequency can also reflect the characteristics of individuals with certain brain pathologies. In their study, Angelakis *et al.* [68] found that individuals with TBI have lower alpha peak frequency values than healthy individuals in the eyes open resting state. It has also been shown that the alpha peak frequency is strongly associated with various cognitive performance variables, such as sentence processing speed.

When the existing research is evaluated, the relationship between the increase in abnormal EEGs and the number of matches can be considered as a result of the increase in the number of punches received due to the increasing number of matches [63]. The level of damage appears according to the severity of the blow received to the head. In boxing, a high-intensity punch to the head can cause severe damage to the opponent and knock them out. From this perspective, the reason for the occurrence of electroencephalographic disorders and abnormal EEG records in boxers who have experienced punch drunkenness and have been knocked out in the studies might be the intense punch blows to the head region [64]. In boxing, success is determined by the points obtained with punch hits. Therefore, an unsuccessful boxer receives more punches than a successful boxer. Each punch hit ultimately results in damage. As a result, the reason why the EEG records of unsuccessful boxers are more irregular than successful boxers might be regarded as a result of receiving more punches [65]. Overall, it is evident that the impacts sustained in sports involving high physical contact, such as boxing, have significant effects on brain health. Research indicates that as the number of head impacts increases, the likelihood of neurological disorders and EEG abnormalities also rises. These findings underscore the critical importance of protective techniques and safety measures during competitions while also highlighting the need for further precautions to safeguard long-term brain health.

Literature includes research where EEG levels are observed normally in amateur boxers and no EEG abnormalities are detected. Additionally, in the study conducted by Brooks *et al.* [69], a 5- to 10-minute eyes-closed resting EEG was recorded following sports-related head trauma. The results showed significant differences in Brain Function Index between athletes who had sustained head trauma and healthy participants within 72 hours of the injury. However, by the end of the 45-day follow-up period, these significant differences in the Brain Function Index were no longer observed. This return of the Brain Function Index in athletes with head trauma to the levels of the control group suggests that a recovery process has taken place. The boxers participating in our study have not been involved in boxing for 4.3 ± 1.33 years. It is known that during the period they were actively boxing, they practiced this sport as amateurs and, therefore, carried out their matches under the rules of amateur boxing by wearing helmets and protective equipment. In addition, these individuals have not received any blows to the head region during the last 4.3 ± 1.33 years. In light of this information, no statistically significant difference was observed when compared with the healthy control group regarding the values of alpha frequency of spectral powers, and the idea that this may be the result of a recovery process can also emerge. When looked at in conclusion, our research results overlaps with the literature and supports existing research.

When the fNIRS data of the participants were evaluated between groups, a significantly lower activation level was detected on the right dmPFC during the congruent task of the Stroop test and on the left dmPFC during the incongruent task in boxers compared to the healthy control group. Also, when the activation occurring during the Stroop test was examined in general, significantly lower activation was recorded on the right and left dmPFC as well as on the left dlPFC/vlPFC/vmPFC/OFC regions in boxers compared to the healthy control group.

Helmich *et al.* [70] asserted that athletes who have sustained brain concussions often display deficits in postural stability and show lower cerebral blood flow in the frontal cortices when experiencing post-concussion symptoms. However, it is reported that it is unclear whether functional brain oxygenation decreases during postural control tasks in symptomatic athletes' post-concussion. They conducted research in this context, comparing the brain oxygenation patterns in the frontal cortices of symptomatic patients. In the study, 62 athletes who had experienced brain concussions (n = 31 symptomatic, n = 31 asymptomatic) were investigated over four sessions. Brain oxygenation was assessed in the frontopolar cortices using fNIRS. The results revealed a significant decrease in the amount of HbO_2 within the left hemispheric frontopolar cortex in symptomatic patients. Helmich *et al.* [71] also examined individuals who had experienced brain concussion and healthy controls to study the hemodynamic response in the frontal brain regions. In this context, the study involved

17 participants, consisting of 10 females and 7 males, with TBI and 8 healthy individuals, including 6 females and 2 males. The study found that the participants who had sustained a brain concussion demonstrated decreased working memory performance and brain oxygenation, thereby concluding a deterioration and decrease in memory functions. Memmini *et al.* [72] investigated the effects of concussion on attention using fNIRS as part of their research on brain damage. In this context, patients who had suffered a brain concussion and a healthy control group were examined within 72 hours after injury. Participants completed an attention task on a computer during fNIRS imaging. Consequently, patients exhibited lower brain activation compared to healthy controls.

Sharma *et al.* [73] studied 21 retired rugby players with a history of TBI and 23 healthy controls. Cerebral hemodynamic changes were examined using fNIRS. The control group demonstrated higher HbO_2 levels compared to the retired rugby players. A decrease in HbO_2 levels and an increase in HHb levels were observed in the left middle frontal gyrus of retired rugby players compared to the healthy control group. As a result, a lower cerebral hemodynamic response was identified in participants with a history of TBI compared to healthy controls. Chang *et al.* [74] conducted a study to identify the extent of executive function damage in the PFC in individuals with neurocognitive disorder following TBI. They applied the Stroop test to 37 patients and 60 healthy controls, examining HbO_2 levels under the surveillance of a 22-channel fNIRS. The results revealed that during the Stroop test, patients exhibited significantly higher error rates and longer reaction times compared to healthy controls. An examination of brain activation maps showed lower activation in the patient group during the Stroop test.

Benmore [75] sought to understand how head trauma affected relative changes in HbO_2, HHb, total hemoglobin (tHb) and hemoglobin difference (Hbdiff) in the left and right prefrontal cortex (LPFC and RPFC). A commonly used head trauma test, the King-Devick (KD) test, and an fNIRS device were used in this context. He examined 22 healthy participants and, during a university rugby match, 17 athletes who had experienced moderate head trauma and 5 athletes who had experienced severe head trauma. As a result, it was observed that following moderate head trauma, both the Hbdiff and the HbO_2 levels were significantly lower compared to baseline in the RPFC. After severe head trauma, the Hbdiff was significantly lower, and the level of HHb in the RPFC was significantly higher. Taken together, these findings indicate a decrease in activation in the RPFC following a rugby match. However, no significant difference was observed in the completion time results of the King-Devick (KD) test among the groups.

Upon a review of the existing literature, it is observed that participants with a history of TBI present a diminished cerebral hemodynamic response, and they exhibit reduced activation during the Stroop test. As per our research findings, boxers demonstrate significantly lower cerebral activation levels in the right dmPFC during the congruent task of the Stroop test and in the left dmPFC during the incongruent task compared to the healthy control group. Additionally, when the overall activation during the Stroop test was examined, boxers showed significantly lower activation in the right and left dmPFC and additionally, in the left dlPFC/vlPFC/vmPFC/OFC regions compared to the healthy control group. The results obtained align with the existing studies in the literature. The presence of an activation difference between our participant group, consisting of boxers and healthy controls, from a neurobiological standpoint within the CNR method, and this difference remaining as a lower response for boxers compared to the healthy control group, could suggest that it might be a consequence of the punches received during active boxing life. The fact that similar results are obtained in the literature on research conducted on individuals who have suffered TBI further strengthens this idea.

When the participants' Stroop test results were evaluated, boxers had a lower error rate for both congruent and incongruent tests, but it was not significant. When the reaction times for the congruent and incongruent tests were examined, it was observed that the healthy group had lower reaction times, but this one also didn't reach a statistically significant level.

Erik *et al.* [76], in their study to determine whether there is acute traumatic brain injury (ATBI) in boxers, applied the Stroop test to 38 amateur boxers and 28 control group boxers after the boxing match. Among the 38 boxers who fought, it was observed that the subjects who were knocked out and technically knocked out had a lower Stroop test speed than the other boxers. However, no significant difference was observed in terms of Stroop test success between the match group and the control group boxers. Banks *et al.* [77] observed 141 professional fighters by applying the Stroop test with the aim of examining the effect of professional fighting (boxing and mixed martial arts) on brain health and whether the level of education is protective against cognitive losses in combat athletes. In conclusion, no relationship was found between the duration of the boxing career and the reaction time containing the Stroop task. They expressed that this was surprising and attributed it to the fact that the participants had been engaging in combat sports for a short time. They also believe that a significant difference could be found in future studies involving retired boxers. Querzola *et al.* [78] aimed to determine the relationship between the neuropsychological profiles of active American football players and TBI. The cognitive performances in neuropsychological tests of 20 American football players and a healthy control group consisting of 19 people were compared. As a result, athletes with a career longer than 7 years showed a significantly poorer result in the Stroop test compared to the ones who had a career of 7 years or shorter. The researchers think that this could be due to the degradation of cognitive abilities as a result of minor head traumas frequently repeated over a long period of time. However, no significant difference was found in terms of neuropsychological test performance between the groups. Ellemberg *et al.* [79] examined female soccer players who had experienced a brain concussion for the first time, 6–8 months after their injuries, and compared them with a healthy control group. As a result of the Stroop test applied to the subjects, it was determined that the sportsman who had a brain concussion showed a significantly longer reaction time than the healthy individuals.

There are also studies suggesting no correlation between the length of a boxing career and reaction time within the context of the Stroop task in the literature. Conversely, some studies report significantly poorer performance on the Stroop test for contact sports athletes who have a career exceeding seven years compared to those with a career of seven years or less. Moreover, research has reported that athletes who have experienced a concussion exhibit significantly later reaction times on the Stroop task than the control group. The severe impact of punches to the head in boxing might inflict substantial impairment on the opponent. From this perspective, research suggests that the slower Stroop test completion speeds of athletes who have experienced a knockout or technical knockout, compared to those who have not, may be due to the severe punches they received to the head. Furthermore, no significant difference was observed in Stroop test performance between boxers who have not experienced a knockout during a match and boxers in the control group. This can be another piece of evidence suggesting the impact of punch intensity on cognitive performance. The lack of a statistically significant difference in Stroop test performance between the boxers participating in our research and healthy individuals might be due to the former's amateur-level involvement in boxing, where protective headgear is used, and their disengagement from boxing for 4.3 ± 1.33 years. From this perspective, it appears that the results obtained align with and support the findings within the existing literature. The study has several limitations. First, the fact that the participants were amateur boxers who wore protective headgear during matches curbs the generalizability of the results. This factor may hinder a full understanding of the long-term neurological effects of boxing. Additionally, the participants had not been actively boxing for a significant period of time, which may have reduced the potential impact of brain damage on their cognitive performance. Another limitation is the relatively small sample size (10 retired boxers and 10 healthy controls), which may restrict the statistical power of the findings and limit the ability to generalize the results to larger populations. Future studies that include a larger sample size and professional boxers could expand the scope of the findings and allow for a more comprehensive evaluation of the long-term neurological effects of boxing.

5. Conclusions

In conclusion, this study reveals that retired elite amateur boxers exhibit significantly lower brain activation, particularly in the PFC, during the Stroop test compared to healthy individuals. While no significant differences were found in the alpha frequency (α) of spectral powers (μV^2) during the resting state, the reduced activation levels recorded during the Stroop test suggest that boxing careers may have lasting effects on the brain. This highlights the need for serious consideration of the long-term neurological impacts in contact sports such as boxing. Furthermore, the importance of implementing more advanced safety measures to protect the brain health of boxers is emphasized. These findings underscore the necessity for further research into the long-term neurological effects of boxing.

AVAILABILITY OF DATA AND MATERIALS

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

AUTHOR CONTRIBUTIONS

MSÇ—was the organizer of the study and conducted measurements, analyzed data, and developed the manuscript. MK—supervised all analyses and revised and edited the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Prior to measurements, approval from the "Ethics Committee of Atatürk University Faculty of Sport Sciences" was granted for the present research (Date: 19 August 2021, No: E-70400699-000-2100215844). Additionally, before the data collection process, participants were provided with detailed information about the test procedures. Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

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CONFLICT OF INTEREST

Both authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors. The authors declare that they have no competing interests.

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