

# **Skill development methods in open-skill sports**

/Opportunities for cognitive skill enhancement in race car drivers/

**Abstract of PhD Thesis**

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Budapest  
2025

## 1.Introduction

Open-skill sports — such as ball games, combat sports, and motor racing — take place in environments characterized by constantly changing, dynamic, and unpredictable stimuli. In these sports, success is not determined solely by physical capacity but also relies heavily on cognitive abilities, including attention, decision-making, working memory, and anticipation. Contemporary sport psychology research increasingly emphasizes that enhancing cognitive skills is a key factor in optimizing performance in open-skill disciplines (Heilmann, Weinberg, & Wollny, 2022). Motorsport falls within this category, encompassing various competitive activities involving motorized vehicles on land or water. These include car and motorcycle racing as well as powerboat competitions, which are organized across multiple formats such as road racing, rally, and drag racing (Trzesniowski, 2021). The majority of studies in motorsport have traditionally focused on engineering developments, vehicle setups, and safety analyses, aiming to improve both performance and spectator experience, or on sociological aspects such as sustainability and public health implications (Dingle, 2009; Dias & Júnior, 2022). In contrast, human-centered research on motorsport athletes remains limited compared to other sports (Potkanowicz & Mendel, 2013; Filho, Tenenbaum, & Yang, 2015; Potkanowicz, 2019). Yet, optimizing the performance of racing drivers requires a comprehensive understanding of the multitude of factors that may directly or indirectly influence outcomes. The purpose of this review is to provide an integrative perspective, with a particular focus on the complex interactions between external and internal determinants, such as physical and mental workload, heat stress, noise exposure, and the quality of airflow within the vehicle (Reid & Lightfoot, 2019). Heat stress elevates heart rate and core temperature while reducing heart rate variability, reflecting diminished parasympathetic and heightened sympathetic nervous system activity. Drivers are exposed to considerable thermal strain due to high ambient temperatures, humidity, and fire-resistant clothing, which can lead to dehydration, impaired performance, and cognitive dysfunction. Acclimatization strategies and cooling technologies are therefore recommended to mitigate these effects. Noise exposure, especially at high frequencies and over prolonged durations, can increase blood pressure and cortisol levels while impairing cognitive performance. In motorsport, the combined noise of engines, airflow, and tires can hinder both attention and in-car communication, with sound levels of 130–140 dB posing a risk of hearing damage. Earplugs, acoustic barriers, and circuit modifications are among the strategies that may reduce such risks. Furthermore, the physical demands of racing are intensified by the G-forces experienced during cornering, braking, and acceleration, which can exceed 5G. These

forces impose substantial strain on the head, neck, and cardiovascular system, potentially causing visual disturbances, dizziness, or loss of consciousness. Drivers employ specific straining maneuvers to maintain blood circulation, while in accidents, forces up to 50–100G may occur, with survival depending on both safety systems and the athlete’s physical preparedness. Racing also imposes high musculoskeletal demands, particularly on the trunk, upper body, and neck muscles, which are critical in counteracting G-forces. Different racing disciplines place varying physical requirements on athletes, necessitating tailored conditioning programs. During competition, heart rate often reaches 74–95% of maximum, reflecting the combined effects of high metabolic demand and psychological stress. Drivers must make rapid and precise decisions at high speed while continuously processing visual, auditory, and physical cues. Empirical studies suggest that experienced drivers possess superior visual perception and spatial awareness, which translate into enhanced performance. Neuroimaging research further indicates that professional drivers exhibit increased activation and gray matter density in specific brain regions associated with these skills. Such findings underscore the neural adaptations that support high-level racing performance. Motor-cognitive training programs appear to be an effective means of fostering both physical and cognitive development in drivers. Accordingly, training regimens should integrate sport-specific physical demands with cognitive challenges to maximize performance optimization and transfer effects.

## 2.Objectives

The central theme of my research is the development of cognitive abilities in race car drivers, both in movement-based and resting environments. The primary aim is to obtain insights into the extent of cognitive improvement within an athletic population, with particular emphasis on race car drivers. Furthermore, my research seeks to establish methods that may support the attainment and maintenance of enhanced mental performance in complex environments and under challenging conditions. The objective of my first study was to determine the effects of a six-week agility training program, based on light stimuli, on the physiological and cognitive abilities of race car drivers. The program was specifically designed to model the complex physical and cognitive demands of motorsport competition within a controlled laboratory setting. In my second study, I examined the feasibility and effectiveness of an innovative neurofeedback (NF) device, the neuroMoon (nM), on cognitive performance, comparing it with one of the most widely used perceptual-cognitive training (PCT) methods applied in both sports and rehabilitation contexts, the NeuroTracker (NT). The central question of this research was

whether it is possible to implement a system that operates on brain signals recorded above the frontal and occipital cortices.

## 2.1 Hypotheses

### 2.1.1 Hypotheses of the first study

**H1:** I hypothesized that the visual search performance of the experimental group would improve on the Visual Search Test (LVT).

**H2:** I hypothesized that the reaction time of the experimental group would improve on the STROOP test.

**H3:** I hypothesized that no change would occur in visual memory performance on the Visual Memory Test (VISGED).

**H4:** I hypothesized that no change would occur in the performance of the Time and Motion Anticipation Test (ZBA).

**H5:** I hypothesized that the error rate would decrease in the experimental group on the Determination Test (DT).

**H6:** I hypothesized that the rate of correct responses would increase in the experimental group on the DT.

**H7:** I hypothesized that physiological performance (HRmax, GETHR) would improve in the experimental group as a result of the agility training program.

**H8:** I hypothesized that the level of relative maximal oxygen uptake ( $VO_{2max}$ ) would increase in the experimental group.

**H9:** I hypothesized that body fat percentage (BF%) would decrease in the experimental group.

**H10:** I hypothesized that heart rate recovery (HRR) would improve in the experimental group.

**H11:** I hypothesized that no change would occur in estimated muscle mass (MM%) in the experimental group.

### 2.1.2 Hypotheses of the second study

**H1:** I hypothesized that working memory performance in the nM group would improve on the Backward Digit Span Backwards (BDST) compared to the control-conditioned group (CCG), but there would be no difference compared to the NT group.

**H2:** I hypothesized that reaction time in the nM group would improve on the STROOP test (word reading and color naming conditions) compared to the CCG, but there would be no difference compared to the NT group.

**H3:** I hypothesized that the number of errors in the nM group would decrease on the STROOP test (word reading and color naming conditions) compared to the CCG, but there would be no difference compared to the NT group.

**H4:** I hypothesized that the proportion of missed responses in the nM group would decrease on the DT compared to the CCG.

**H5:** I hypothesized that the proportion of correct responses in the nM group would increase on the DT compared to the CCG, but there would be no difference compared to the NT group.

**H6:** I hypothesized that cognitive flexibility in the nM group would improve on the SWITCH test compared to the CCG, but there would be no difference compared to the NT group.

### 3.Methods

#### 3.1. Methods of the first study

The first study was conducted within the framework of a single-blind, randomized controlled trial, with a sample of twenty-four race car drivers from various disciplines (rally, rallycross, touring cars, Formula 4). Inclusion criteria required at least five years of racing experience, participation in international championships or placement among the national elite in the previous season, and the absence of neurological or sensorimotor impairments. Sample size was calculated a priori using the G\*Power 3.1.7 program: assuming a medium effect size, a Type I error rate of 0.05, and a statistical power of 0.80, at least twenty participants were required to detect significant differences. This condition was met with the inclusion of twenty-four drivers. Recruitment was carried out through the Fit4Race sports science center, where the drivers had not previously participated in cognitive or agility training, ensuring that the applied procedures were novel to them. The experimental protocol consisted of three main phases: baseline assessment, intervention, and post-test assessment. During baseline measurements, participants underwent anthropometric assessment, a cognitive test battery (Visual Search Test, Stroop Test, Visual Memory Test, Time and Motion Anticipation Test, Determination Test), and a spiroergometric test. Cognitive assessments were conducted by a psychologist, physiological testing by an exercise physiology specialist, and anthropometric assessments by an ISAK-licensed expert, thereby ensuring measurement reliability. Assessments took place over several days under standardized conditions, with participants' alcohol consumption and caffeine intake controlled to eliminate confounding factors. The intervention involved a six-week training program for the experimental group, consisting of two 60-minute sessions per week, with 48–72 hours of rest between sessions. The training was supervised by specialists from Fit4Race under the continuous oversight of the principal investigator. The control group did not receive any intervention. Participants in both groups were instructed not to engage in any additional cognitive or motor training, nor to alter their daily routines or dietary habits during the study. Post-test assessments were carried out two days after the final training session and were identical to the baseline procedures, enabling direct comparison of pre- and post-intervention outcomes. The study adhered to the ethical standards of the Declaration of Helsinki, was approved by the Ethics Committee of the Hungarian University of Physical Education and Sport Sciences (TE-KEB/No11/2020), and was designed and conducted in accordance with the CONSORT guidelines. The research thus ensured an adequate sample, a professional measurement protocol, a structured intervention, and post-test evaluations,

forming the basis for statistical analyses and the evaluation of intervention effectiveness. Statistical analyses were conducted using SPSS 22.0 software. The normality of the data distribution was verified with the Shapiro–Wilk test, and logarithmic transformation was applied when necessary. The effects of the six-week training program were analyzed using mixed-design analyses of variance (ANOVA) with group (EXP, CON)  $\times$  time (pre, post) factors, followed by post hoc tests for physical, cognitive, and anthropometric variables. For cognitive tests (STROOP, ZBA), results were analyzed with a mixed-design ANOVA including group  $\times$  time  $\times$  task complexity (rest, during exercise) factors. Agility, reaction time, and heart rate changes were evaluated using repeated-measures ANOVAs (rmANOVA) with Bonferroni correction. Sphericity was tested with Mauchly’s test, and Greenhouse–Geisser or Huynh–Feldt corrections were applied when necessary. Effect sizes were reported using partial eta squared ( $\eta^2$ ) for ANOVA and Cohen’s *d* for paired *t*-tests. Statistical significance was set at  $p < 0.05$ .

### 3.2 Methods of the second study

In the second study, sample size calculations were performed using the G\*Power 3.1.7 program, which indicated that a minimum of 24 participants would be required to detect significant differences. Ultimately, a total of 31 open-skill athletes participated in the study, including race car drivers ( $n = 11$ ), football players ( $n = 8$ ), handball players ( $n = 4$ ), and basketball players ( $n = 8$ ). Participants were randomly assigned into three groups: neuroMoon (nM,  $n = 11$ ), neuroMoon sham or conditioned control group (CON,  $n = 10$ ), and NeuroTracker (NT,  $n = 10$ ). All participants were active athletes, reported no neurological or sensorimotor deficits, and received no financial compensation for their involvement. The study was conducted in accordance with ethical standards, following the principles of the Declaration of Helsinki, and received approval from the Ethics Committee of the Hungarian University of Physical Education and Sport Sciences (TE-KEB/No36/2022). Participants were informed of the protocol both orally and in writing, and provided written informed consent prior to inclusion. The study was carried out at the Fit4Race training center, a facility specifically designed for testing athletes and motorsport competitors. Prior to testing, participants were instructed to abstain from alcohol consumption for 24 hours and from coffee consumption on the morning of the assessment. The assessment protocol included the Digit Span Backwards (DSB) and three cognitive tests from the Vienna Test System (VTS). The VTS is a widely applied tool in sports science research for objectively measuring athletes’ psychomotor and

cognitive abilities. Before each test, participants completed a practice phase in which they received immediate feedback on errors, ensuring accurate task comprehension. The intervention phase began one week after the baseline assessments and lasted for four weeks, comprising a total of 12 sessions with three training sessions per week, each separated by 48–72 hours of rest. Athletes participated in three different cognitive training programs. The first was the EEG-based neuroMoon system, which employed four electrodes placed according to the international 10–20 system, allowing high-quality data acquisition. The device used dry electrodes, which ensured quick and comfortable placement and eliminated the need for conductive gel. The second group (CON) received neuroMoon sham, a conditioned control training, while the third group engaged in the NeuroTracker program, which focused on enhancing visuocognitive abilities. Two days after completing the training program, participants underwent the same assessment protocol in the same sequence and under identical conditions as at baseline. This ensured direct comparability of pre- and post-intervention outcomes and enabled an objective evaluation of the effects of the four-week cognitive training. The aim of the study was to explore the extent to which technology-based cognitive training methods could enhance the cognitive performance of open-skill athletes, and to assess their potential as effective complementary tools in athletic preparation. Statistical analyses were performed using SPSS 22.0 software. Data normality was checked with the Shapiro–Wilk test and by visual inspection of histograms, with logarithmic transformation applied where necessary. The effects of the cognitive training programs were evaluated using repeated-measures analysis of variance (ANOVA<sub>m</sub>) with time (PRE, POST) × group (nM, NT, CON) as factors. Multiple comparisons were corrected with the Bonferroni method, and EEG metrics (SMR, T, SMR/T) were analyzed using ANOVA<sub>m</sub> as well. Complementary analyses included paired t-tests and calculation of Cohen’s *d* effect sizes, while effect sizes were also reported using partial eta squared ( $\eta^2$ ). The effectiveness of neurofeedback training was further tested with the Mann–Whitney U test, and correlation analyses were conducted to explore associations between behavioral and EEG changes. Statistical significance was set at  $p < 0.05$ , and graphs were produced using JASP version 0.17.1.

## 4.Results

### 4.1 Results of the first study

Both performance indicators and physiological measures were influenced by the agility training performed during the six-week program. Statistical analyses revealed main effects of training

( $F_{11,121} = 22.4$ ,  $p < 0.001$ ,  $\eta^2 = 0.67$ ) and set ( $F_{4,44} = 1225.2$ ,  $p < 0.001$ ,  $\eta^2 = 0.99$ ), as well as a training  $\times$  block interaction ( $F_{44,484} = 8.3$ ,  $p < 0.001$ ,  $\eta^2 = 0.43$ ) on agility performance. Post hoc rmANOVA indicated that participants significantly improved between the 1st and 2nd, and between the 11th and last training sessions ( $p < 0.001$ ). With the exception of session 3, drivers demonstrated higher agility performance in every training session compared to session 1 ( $p < 0.001$ ), regardless of training block. Considering that each block lasted one minute longer than the previous, it was unsurprising that participants consistently improved their agility performance from block to block ( $p < 0.001$ ), irrespective of training phase. The agility training program also induced changes in reaction time, as indicated by main effects of training ( $F_{11,121} = 30.3$ ,  $p < 0.001$ ,  $\eta^2 = 0.73$ ) and block ( $F_{4,44} = 6.4$ ,  $p < 0.001$ ,  $\eta^2 = 0.37$ ), and a training  $\times$  block interaction ( $F_{44,484} = 1.5$ ,  $p = 0.027$ ,  $\eta^2 = 0.12$ ). Post hoc rmANOVA revealed significant improvements between the 1st and 2nd, the 3rd and 4th, and the 4th and 5th training sessions. Reaction times were worse during the 11th training and similar to the 8th session ( $1.36 \pm 0.12$  ms vs.  $1.36 \pm 0.11$  ms). Nevertheless, drivers consistently exhibited shorter reaction times across all training sessions compared to session 1 ( $p < 0.001$ ), including the final (12th) session, regardless of block, indicating improved reaction speed in executing the agility task (Figure 21). Furthermore, results improved in every block compared to block 1 ( $p < 0.001$ ), independent of training stage. Although mean HR and HRmax remained unchanged throughout the training program, HRR (heart rate recovery) showed main effects of training ( $F_{2,22} = 5.7$ ,  $p = 0.010$ ,  $\eta^2 = 0.34$ ) and block ( $F_{2,22} = 3.9$ ,  $p = 0.034$ ,  $\eta^2 = 0.26$ ). Post hoc analyses revealed higher HRR values at session 6 ( $46.0 \pm 7.2$  bpm) and session 12 ( $47.6 \pm 7.2$  bpm) compared to session 1 ( $40.92 \pm 7.8$  bpm), regardless of training block. Specifically, a main effect of time was observed for LVT reaction time ( $F_{1,22} = 4.3$ ,  $p = 0.05$ ,  $\eta^2 = 0.16$ ) and LVT correct responses ( $F_{1,22} = 7.8$ ,  $p = 0.011$ ,  $\eta^2 = 0.26$ ). Post hoc analyses indicated reduced RT and more correct responses after the intervention, independent of group. Moreover, a group  $\times$  time interaction was found for LVT ( $F_{1,22} = 5.2$ ,  $p = 0.033$ ,  $\eta^2 = 0.19$ ). Post hoc tests showed that LVT RT decreased in the EXP group ( $p = 0.038$ ,  $d = 0.61$ ) but remained unchanged in the CON group ( $p = 0.800$ ,  $d = 0.05$ ), suggesting that the agility training program improved drivers' visual orientation and selective visual attention. Mixed ANOVA revealed group  $\times$  time interactions for both RT ( $F_{1,22} = 8.7$ ,  $p = 0.007$ ,  $\eta^2 = 0.28$ ) and incorrect responses ( $F_{1,22} = 10.6$ ,  $p = 0.004$ ,  $\eta^2 = 0.32$ ) in the STROOP color-naming condition. Post hoc analysis showed slightly increased RT in the CON vs. EXP group ( $p = 0.048$ ,  $d = 0.05$ ) and fewer incorrect responses in the EXP vs. CON group ( $p < 0.001$ ,  $d = 0.96$ ). In the word-reading condition, a significant group  $\times$  time interaction was observed for RT ( $F_{1,22} = 8.3$ ,  $p = 0.009$ ,  $\eta^2 = 0.27$ ),

with post hoc analysis showing decreased RT in the EXP group ( $p = 0.028$ ,  $d = 0.60$ ), while the CON group remained unchanged ( $p = 0.134$ ,  $d = 0.56$ ). Furthermore, a main effect of time ( $F_{1,22} = 4.7$ ,  $p = 0.041$ ,  $\eta^2 = 0.18$ ) and group  $\times$  time interaction ( $F_{1,22} = 6.8$ ,  $p = 0.016$ ,  $\eta^2 = 0.24$ ) were found for incorrect responses. Post hoc analysis revealed reduced errors in the CON group ( $p = 0.021$ ,  $d = 1.00$ ), while the EXP group showed no change ( $p = 0.819$ ,  $d = 0.09$ ), likely due to high baseline variability. No STROOP interference effect was observed in either color-naming or word-reading conditions ( $p > 0.05$ ). No main effect of time or group  $\times$  time interaction was observed for VISGED and ZBA ( $p > 0.05$ ), indicating that the agility training did not alter visual memory performance or time/movement anticipation. Similarly, no changes were detected in the CON group for these measures. However, a main effect of time ( $F_{1,22} = 6.4$ ,  $p = 0.019$ ,  $\eta^2 = 0.22$ ) and a group  $\times$  time interaction ( $F_{1,22} = 18.5$ ,  $p < 0.001$ ,  $\eta^2 = 0.46$ ) were found for correct responses in the DT. Post hoc analysis showed increased correct responses in the EXP group ( $p = 0.05$ ,  $d = 0.77$ ) but decreased scores in the CON group ( $p = 0.04$ ,  $d = 0.12$ ) compared to baseline ( $267.3 \pm 32.9$ ,  $265.3 \pm 48.1$ , respectively). In addition, the EXP but not the CON group showed fewer missed responses, as indicated by a group  $\times$  time interaction ( $F_{1,22} = 8.9$ ,  $p = 0.007$ ,  $\eta^2 = 0.29$ ) and post hoc paired t-tests (EXP:  $p = 0.034$ ,  $d = 0.78$ ; CON:  $p = 0.087$ ,  $d = 0.23$ ). According to statistical analysis, body weight (BW) decreased in the EXP group (from  $79.3 \pm 10.9$  to  $77.2 \pm 10.3$  kg) but increased in the CON group (from  $78.8 \pm 9.4$  to  $79.7 \pm 9.4$  kg), as shown by a group  $\times$  time interaction ( $F_{1,22} = 21.9$ ,  $p < 0.001$ ,  $\eta^2 = 0.50$ ) and post hoc tests ( $p = 0.004$ ,  $d = 0.20$ ;  $p = 0.004$ ,  $d = 0.10$ , respectively). As expected, height (BH) remained unchanged in both groups ( $p > 0.05$ ). While no changes were found in estimated muscle mass (EMM%) ( $p > 0.05$ ), a main effect of time ( $F_{1,22} = 47.3$ ,  $p < 0.001$ ,  $\eta^2 = 0.68$ ) and group  $\times$  time interaction ( $F_{1,22} = 70.4$ ,  $p < 0.001$ ,  $\eta^2 = 0.76$ ) were detected for body fat percentage (BF%). Post hoc analysis indicated lower post-intervention BF% in the EXP group ( $p < 0.001$ ,  $d = 0.57$ ), but higher BF% in the CON group ( $p = 0.041$ ,  $d = 0.05$ ). Both HRmax and GETHR showed main effects of time ( $F_{1,22} = 7.2$ ,  $p = 0.014$ ,  $\eta^2 = 0.25$ ;  $F_{1,22} = 17.0$ ,  $p < 0.001$ ,  $\eta^2 = 0.44$ , respectively) and group  $\times$  time interactions ( $F_{1,22} = 22.1$ ,  $p < 0.001$ ,  $\eta^2 = 0.50$ ;  $F_{1,22} = 30.5$ ,  $p < 0.001$ ,  $\eta^2 = 0.58$ , respectively). Post hoc tests indicated higher post-intervention HRmax during the maximal graded cardiorespiratory test in the EXP group ( $p = 0.002$ ,  $d = 0.45$ ) and lower values in the CON group ( $p = 0.033$ ,  $d = 0.40$ ). Furthermore, GETHR was higher in the EXP group compared to baseline ( $p < 0.001$ ,  $d = 1.2$ ), while it remained unchanged in the CON group ( $p = 0.086$ ,  $d = 0.24$ ). Mixed ANOVA revealed a main effect of time ( $F_{1,22} = 25.4$ ,  $p < 0.001$ ,  $\eta^2 = 0.53$ ) and a group  $\times$  time interaction ( $F_{1,22} = 43.1$ ,  $p < 0.001$ ,  $\eta^2 = 0.66$ ) for VE, with post hoc analysis showing higher post-intervention

VE values in the EXP group ( $p < 0.001$ ,  $d = 1.62$ ), while no changes occurred in the CON group ( $p = 0.057$ ,  $d = 0.28$ ). Although BF remained unchanged ( $p > 0.05$ ), a main effect of time ( $F_{1,22} = 28.3$ ,  $p < 0.001$ ,  $\eta^2 = 0.56$ ) and a group  $\times$  time interaction ( $F_{1,22} = 41.5$ ,  $p < 0.001$ ,  $\eta^2 = 0.65$ ) were found for  $VO_{2max}$ . Post hoc analyses showed increased  $VO_{2max}$  in the EXP group ( $p < 0.001$ ,  $d = 0.85$ ) but decreased values in the CON group ( $p = 0.029$ ,  $d = 0.17$ ).

#### 4.2 Results of the second study

A significant main effect of time was observed in the interference (IF) trend ( $F_{1,28} = 10.943$ ,  $p = 0.003$ ,  $\eta^2 = 0.281$ ) and in median reaction time for both the congruent (BL) ( $F_{1,28} = 6.390$ ,  $p = 0.017$ ,  $\eta^2 = 0.186$ ) and incongruent (IF) tasks ( $F_{1,28} = 8.045$ ,  $p = 0.008$ ,  $\eta^2 = 0.223$ ) in the word-reading condition of the STROOP task. Comparison of pre- and post-intervention measurements indicated faster interference trends (pre:  $0.204 \pm 0.133$  vs. post:  $0.163 \pm 0.113$  s, Cohen's  $d = 0.479$ ) and shorter median reaction times in the congruent task ( $0.604 \pm 0.076$  vs.  $0.583 \pm 0.073$  s,  $d = 0.445$ ) and the incongruent task ( $0.807 \pm 0.178$  vs.  $0.746 \pm 0.155$  s,  $d = 0.761$ ), regardless of group. Furthermore, significant main effects of time were observed in the color-naming condition of the STROOP task for both the congruent ( $p < 0.001$ ,  $d = 0.859$ ) and incongruent ( $p = 0.026$ ,  $d = 0.420$ ) tasks, without differences between groups. Regarding the SWITCH task, a significant main effect of time was found for working time ( $F_{1,28} = 17.968$ ,  $p < 0.001$ ,  $\eta^2 = 0.385$ ) and for mean reaction time to incongruent stimuli ( $F_{1,28} = 15.989$ ,  $p < 0.001$ ,  $\eta^2 = 0.363$ ), in both the repeat task ( $F_{1,28} = 9.573$ ,  $p = 0.004$ ,  $\eta^2 = 0.255$ ) and the switch task ( $F_{1,28} = 4.558$ ,  $p = 0.042$ ,  $\eta^2 = 0.140$ ). Comparison of pre- and post-intervention measurements showed faster working times and shorter mean reaction times after the intervention for all the mentioned variables ( $p < 0.05$ ). The Digit Span Backward (DSB) test showed a significant main effect ( $F_{1,28} = 15.218$ ,  $p < 0.001$ ,  $\eta^2 = 0.352$ ), with post-intervention scores ( $6.42 \pm 1.54$ ) higher than pre-intervention scores ( $5.55 \pm 1.43$ ) ( $d = -0.801$ ), independent of group. Moreover, a mixed ANOVA revealed a significant main effect of time for both omissions ( $F_{1,28} = 71.554$ ,  $p < 0.001$ ,  $\eta^2 = 0.719$ ) and correct responses ( $F_{1,28} = 33.541$ ,  $p < 0.001$ ,  $\eta^2 = 0.545$ ) in the DT. Pre- and post-intervention comparisons showed a reduction in omitted responses (pre:  $17.5 \pm 8.3$ , post:  $6.4 \pm 1.5$ ,  $d = 1.311$ ) and an increase in correct responses (pre:  $261.6 \pm 36.1$ , post:  $278.6 \pm 38.7$ ,  $d = -1.020$ ), independent of group. All other cognitive test variables related to the VTS were not significant ( $p > 0.05$ ). Correlation analyses revealed strong positive correlations between SMR and T differences during sessions in both the nM ( $r = 0.969$ ,  $p < 0.001$ ) and control-conditioned nM ( $r = 0.937$ ,  $p < 0.001$ ) groups,

suggesting that SMR increases during training were associated with T increases, regardless of group. Changes in other EEG metrics, as well as the relationships between EEG metrics and game scores, were generally weak ( $r < 0.3$  or  $r > -0.3$ ) in both groups. No differences were found between the nM and control-conditioned NF training groups in EEG metrics (SMR, T, SMR/T ratio) ( $p > 0.05$ ) or game scores ( $p = 0.96$ ) across the individual training sessions.

## 5. Conclusions

### 5.1 Conclusions of the first study

The agility training program improved cognitive performance in certain subtests of the VTS when participants completed them either at rest or during moderate-intensity exercise. Race car drivers performed the STROOP word-reading condition more accurately during exercise compared to at rest. In addition, the intervention elicited favorable changes in several physiological measures, such as HRmax, gas exchange threshold heart rate (GET HR), ventilation, and relative maximal oxygen uptake ( $VO_{2max}$ ) during the maximal incremental cardiorespiratory test. Finally, during the agility task, drivers showed continuously improving performance and decreasing reaction times over the six-week training program. These results suggest that such a short and easily administered training program could potentially contribute to both the physical and mental preparation of race car drivers. However, future research is needed to collect additional scientific data on this relatively underexplored sport to develop effective strategies for enhancing the physical and cognitive abilities of motorsport athletes. We accept our first hypothesis, as reaction time in the visual search test (LVT) of the EXP group significantly decreased after the intervention ( $3.19 \pm 0.38$  ms) compared to baseline ( $3.83 \pm 1.31$  ms), indicating improved visual orientation and selective attention. The second hypothesis is also accepted, since the error rate in the STROOP color-naming task decreased in the EXP group, while no change was observed in the control group (CON). In the word-reading task, the EXP group showed faster reaction times, whereas the reduction in errors occurred in the CON group, which can be explained by high individual variability at baseline. Hypotheses 3 and 4 are rejected, as no main effect of time or group  $\times$  time interaction was found in the visual memory (VISGED) or time/motion anticipation (ZBA) tests, indicating that the training program did not elicit detectable changes in these cognitive performance variables. Hypothesis 5 is accepted, as the EXP group produced more correct and fewer omitted responses in the Determination Test (DT), reflecting improvements in reactive stress tolerance, attention, and rapid response. Hypothesis 6 is rejected, as no significant changes were observed in the

STROOP interference condition under either resting or exercise conditions, indicating that the program did not specifically enhance processing of incongruent stimuli. Hypothesis 7 is partially accepted. No practically meaningful changes were observed in HRmax values, but a significant improvement was detected at the gas exchange threshold (GET) in the EXP group, suggesting a delayed onset of lactate accumulation and attainment at higher intensities. Hypothesis 8 is fully accepted, as the agility training program increased relative maximal oxygen uptake (VO<sub>2</sub>max) and ventilation, indicating favorable cardiovascular adaptations. Hypothesis 9 is rejected, since the program did not significantly change mean or maximal heart rate, indicating that these markers of cardiovascular load capacity were not affected. Finally, hypothesis 10 is accepted, as HRR values significantly improved in the EXP group after the training program, demonstrating enhanced recovery capacity. Overall, our findings indicate that the agility training program effectively contributed to improvements in race car drivers' selective attention, reaction time, stress tolerance, and certain cardiovascular measures, while producing no measurable effects in specific cognitive domains such as visual memory or interference processing.

## 5.2 Conclusion of the second study

The aim of the present study was to investigate the feasibility and effectiveness of a newly developed neurofeedback (NF) system, neuroMoon (nM), in enhancing cognitive performance, compared to a widely used cognitive training tool, Neurotracker (NT). We hypothesized that cognitive improvements following nM training would be comparable to those achieved with NT, suggesting that nM could also benefit athletes seeking to enhance cognitive performance. In line with our hypothesis, statistical analyses primarily revealed main effects of time, with no significant group effects, indicating that both nM and NT contributed similarly to cognitive performance improvements. For instance, both training groups showed faster median reaction times in the STROOP color-naming and word-reading conditions post-training, reflecting enhanced cognitive adaptability and task-switching ability. Based on this, we accept our second hypothesis. In the SWITCH task, participants demonstrated improvements in total working time as well as reaction times for incongruent stimuli, repeat, and switch conditions, indicating enhanced executive functions, particularly task-switching ability. This supports our sixth hypothesis, which we accept. In the Determination Test (DT), both nM and NT training led to fewer omissions (pre:  $17.5 \pm 8.3$ ; post:  $6.4 \pm 1.5$ ;  $d = 1.311$ ) and more correct responses (pre:

261.6 ± 36.1; post: 278.6 ± 38.7; d = -1.020), reflecting improvements in attentional capacity and reactive performance. Accordingly, we accept hypotheses four and five. In the Digit Span Backward (DSB) test, participants in both groups achieved higher post-training scores (6.42 ± 1.54) compared to baseline (5.55 ± 1.43), indicating improvements in cognitive flexibility and working memory, independent of the method applied. However, similar improvements were observed in the control-conditioned group, leading us to only partially accept the first hypothesis. EEG measures (SMR, T, SMR/T ratio) and game scores revealed no significant differences between the active and control-conditioned nM groups ( $p > 0.05$ ), and correlations between variables were weak, suggesting that the short, four-week intervention was insufficient to detect longer-term effects of neurofeedback-based PCT. Overall, our findings indicate that both nM and NT positively influenced reaction time, cognitive flexibility, task-switching ability, and attentional performance. Nevertheless, comparable improvements in the control-conditioned group caution that some gains may be attributable to test familiarization or general learning effects. The significance of our study lies in demonstrating the potential utility of innovative NF tools like nM among athletes. Such training is particularly relevant for race car drivers and athletes in open-skill sports (e.g., ball games), who require rapid decision-making, focused attention, and short reaction times under high load and stressful conditions. While nM may contribute to developing these abilities, further research is needed to explore its long-term effects, incorporate passive control groups, and examine increased training volume. Finally, our results confirm that both NF-based and cognitive training approaches offer promising strategies for enhancing athletes' mental performance. NeuroMoon appears especially promising for spaceflight and other complex environments where cognitive flexibility and rapid decision-making are critical. Future studies should evaluate and validate nM in authentic, real-world conditions, which could be valuable not only for space missions but also for optimizing performance in high-stakes terrestrial scenarios.

## 6. List of publications

List of publications related to the topic of the dissertation:

Horváth, D., Négyesi, J., Győri, T., Szűcs, B., Tóth, P. J., Matics, Z., ... Rácz, L. (2022). Application of a Reactive Agility Training Program Using Light-Based Stimuli to Enhance the Physical and Cognitive Performance of Car Racing Drivers: A Randomized Controlled Trial. *SPORTS MEDICINE-OPEN*, 8(1). <http://doi.org/10.1186/s40798-022-00509-9>

Horváth, D., Négyesi, J., Rácz, M., Győri, T., Matics, Z., Puskin, A., ... Rácz, L. (2023). Feasibility of a novel neurofeedback system: a parallel randomized single-blinded pilot study. *SCIENTIFIC REPORTS*, 13(1). <http://doi.org/10.1038/s41598-023-44545-1>

List of publications not related to the dissertation

Fridvalszki, M., Matlák, J., Kovács, B., Petridis, L., Horváth, D., Havanecz, K., ... Rácz, L. (2022). Reliability Study of a Functional Test for the Offensive Agility Performance in Water Polo. *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH*, 19(16). <http://doi.org/10.3390/ijerph191610040>

MARCELL, F., JÁNOS, M., BÁLINT, K., TIBOR, H., LEONIDAS, P., DONATELLA, D., ... LEVENTE, R. (2023). Vienna Test System measures failed to predict goal and passing efficiency during international water polo matches in world-class-level youth water polo players. *INTERNATIONAL JOURNAL OF SPORT PSYCHOLOGY*, 54(5), 389–403. <http://doi.org/10.7352/IJSP.2023.54.389>

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TÓTH, P. J., GYŐRI, T., SÁFÁR, S., HAVANECZ, K., HORVÁTH, D., & ÖKRÖS, C. (2022). Különböző játéktípussal rendelkező teniszezők mérkőzés statisztikáinak elemzése a 2022-es ausztrál nyílt teniszbajnokság férfi döntősein keresztül. In *XXV. Tavasz Szél Konferencia 2022. Absztraktkötet* (pp. 606–607).

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