Heliyon 10 (2024) e28712

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effects of Fitlight training on cognitive-motor performance in élite judo athletes

M. Campanella [a,1], L. Cardinali [b,c,1], D. Ferrari [d], S. Migliaccio [c,e], F. Silvestri [f], L. Falcioni [g], V. Bimonte [c], D. Curzi [f], M. Bertollo [h,*], L. Bovolon [i], M.C. Gallotta [j], L. Guidetti [f], C. Baldari [a,2], V. Bonavolontà [k,2]

[a] *Department of Theoretical and Applied Sciences, eCampus University, Novedrate, Italy*
[b] *Bone Metabolic Diseases Unit, Department of Experimental and Clinical Biomedical Sciences, University of Florence, Florence, Italy*
[c] *Department of Experimental Medicine, University Sapienza of Rome, Rome, Italy*
[d] *Department of Human Sciences, LinkCampus University, Rome, Italy*
[e] *Department of Movement, Human and Health Sciences, University Foro Italico, 00135, Rome, Italy*
[f] *Niccolò Cusano University, Rome, Italy*
[g] *Department of Health and Exercise Science, Appalachian State University, Boone, NC, United States*
[h] *BIND-Behavioral Imaging and Neural Dynamics Center, Department of Medicine and Aging Sciences, University G. d'Annunzio of Chieti-Pescara, 66100, Chieti, Italy*
[i] *Department of Psychological, Humanistic and Territorial Sciences, University G. d'Annunzio, Chieti-Pescara, Italy*
[j] *Department of Physiology and Pharmacology "Vittorio Erspamer", Sapienza University of Rome, 00185, Rome, Italy*
[k] *Department of Biotechnological and Applied Clinical Sciences, University of L'Aquila, 67100, L'Aquila, Italy*

ARTICLE INFO

Keywords:
Executive functions
Combat sports
High-level training
BDNF

ABSTRACT

Aims: The aims of this study were to verify if a 5-week cognitive-motor training (CMT) using FitlightsTM induced changes in young adult judo athletes compared to a non-intervention group. Specifically, it was verified if CMT influenced executive functions (EFs), physical fitness and brain-derived neurotrophic factor (BDNF) levels. Additionally, athletes' competitive results were compared between groups.

Method: Twenty-seven athletes (14 males and 13 females; age = 19.5 ± 2.0 years) were assigned to the Fitlight (FG) and control (CG) groups which performed 5 weeks of CMT, respectively, including 25 min per day of Fitlight training or traditional judo practice. All participants performed cognitive (flanker task and forward/backward digit span) and fitness tests (counter movement jump, handgrip test, dynamic and isometric chin up). In addition, BDNF was collected by saliva sampling and competitive results after the intervention period were considered.

Results: RM-ANOVA showed significant differences in FG for the accuracy of flanker ($p = 0.028$) and backward digit span ($p < 0.001$). Moreover, significant differences in FG were found for relative dynamic chin up ($p = 0.027$) and counter movement jump ($p = 0.05$). In addition, a significant difference in FG was found for competitive results after the intervention period ($p < 0.01$).

No significant differences were found for BDNF and other cognitive and fitness measures ($p > 0.05$).

---

* Corresponding author.
E-mail address: m.bertollo@unich.it (M. Bertollo).

[1] These authors contributed equally to this paper.

[2] These authors contributed equally to this paper.

https://doi.org/10.1016/j.heliyon.2024.e28712
Received 20 November 2023; Received in revised form 21 March 2024; Accepted 22 March 2024

Conclusion: A 5-week judo-specific CMT improved EFs and motor performance in élite judo athletes. It seems that CMT with Fitlight™ could be considered an additional support to coaches during the training period.

1. Introduction

The family of cognitive processes known as executive functions (EFs) includes inhibitory control, working memory and cognitive flexibility, and they are crucial for many daily activities from childhood to later life stages [1].

Inhibitory control is very difficult for young children and it continues to develop during adolescence [2]. Instead, the ability to remember information develops extremely early; new-borns and young children can remember one or two things for a long time [3]. However, the ability to hold more things in mind or perform any type of mental manipulation takes much longer to develop and has a much longer developmental progression [4,5]. Finally, task switching improves during a child's development and declines with age [6].

These skills, known as basic EFs, are crucial for the growth of high-order EFs like problem solving, reasoning, and planning [1]. Physical activity (PA) and sport practice (SP) have been identified by researchers as such activities that, when combined with the right inputs, could enhance EFs [7,8]. Indeed, since SP typically involves both physical and cognitive participation, the growth of EFs, mostly in children and teenagers, can be linked to playing sports [9,10].

According to recent literature, the development of EFs is age-related and increases in accordance with one's growth [11] until the young adult stage [12]. Conversely, age-related effects on some EFs metrics, such as response accuracy, are still up for discussion [11,13].

Previous studies reported that the typology of SP, i.e., open- or closed-skills sports can differently affect EFs development [14,15]. While closed skill sports are classified as static with predetermined conditions (e.g., swimming or jogging), open skill sports (e.g., team sports or combat sports) are set in a dynamic environment where conditions could alter at any time [15]. Numerous factors and stimuli should be taken into account when practising open-skill sports, that may improve the EFs (i.e. cognitive flexibility or inhibition) [9,10]. Indeed, in a systematic review, Gu et al. [16] examined the effects of open and closed skill exercises on EFs development, finding that open skill exercises had greater impacts on EFs improvement in children and adults. Previous studies reported that both the motor and cognitive areas greatly benefit from the complexity of the open-skill athletic setting [17,18]. In particular, Formenti et al. [18] reported that open-skill sports presented higher inhibitory control (response time and accuracy of the Flanker task) and motor tests than closed-skill sports. These results showed that engaging in open skill sport activities, than closed skill sport activities, may be linked to improved performance on assessments of motor and cognitive fitness. This shows that a sport's environment has a significant impact on a player's physical and mental development.

There is large evidence of a close relationship between open-skill sports and EFs, both in team sports, such as football, basketball or volleyball [19–23] and in individual sports, such as tennis [24] or combat sports, such as judo, karate, and taekwondo [25–28]. All the above-mentioned studies suggest that open-skill sports practice can induce EFs development.

However, Heilmann et al. [15] recently noted how the greater EFs engagement seems to be more tied to the cognitive demands of a sport rather than to the sharp distinction between open and closed skill exercises.

Open-skill sports like martial arts need participants to react in a constantly shifting and hurried environment [14,29]. In fact, grappling and throwing, which are the main techniques used in judo, contribute to the changing conditions and environments [26].

Moreover, the intense level of cognitive demands (such as planning, problem-solving, and shifting) and physical demands (such as cardio-respiratory fitness, muscular strength and endurance, and movement coordination) may aid in the development of EFs by promoting neuroplasticity-related growth factors like brain-derived neurotrophic factor (BDNF) [30,31].

Earlier studies largely examined the impact of martial arts on inhibition, not limiting it to set-shifting. Only a few studies investigated the impact of judo training on EFs, mostly studying children and amateur athletes. It is then to clarify whether Judo training improves EFs in élite athletes as well as in adolescents and young adults [26].

Sensorized light systems, such as Fitlight™, have been used in several studies as a Cognitive-motor training (CMT) to improve EFs [32,33].

Additionally, it has been demonstrated that the Fitlight training system™ (2011) stimulates EFs engagement throughout various sporting activities, optimising athletes' human reaction times [34].

Specifically, during physical training sessions these devices are able to interact with users providing challenging and enjoyable tasks. Moreover Fitlights™ may improve training variability management (such as light colour and stimulus start time). In addition, it enables the creation of customised training plans, allowing coaches to oversee small groups of athletes at once and customise their training. As a result, these tools can aid CMT development and execution, stimulate EFs, and enhance an athlete's strategic decision-making. The ability to activate executive functions (working memory, inhibition, and cognitive flexibility) has led to the development of a wide variety of motor drills [32]. The above-mentioned study found that CMT training procedures improved sports performance and cognition compared to training that relied just on physical activities. In addition, Badau et al. [33] found that open-skill athletes displayed faster reaction times in computerised assessments after a 12-week program of Fitlight-enabled exergames.

Currently, there are no studies that used CMT with Fitlight™ to improve EFs in martial arts, and more specifically, in Judo.

Therefore, the present study examined whether the Fitlight™ training system used to cognitively enrich a massed judo training program, can improve EFs (specifically, response inhibition, working memory, and cognitive flexibility) and physical performance (i.

e., isometric strength, resistance strength of the upper limbs and explosive-elastic strength of the lower limbs) in young adult athletes compared to a non-intervention group. Specifically, the aim of this study was to verify if a 5-week CMT using Fitlight training in young adult judo athletes induced changes on: EFs, physical fitness, BDNF levels, competitive results.

2. Materials and methods

2.1. Participants and study design

A priori analysis with G*Power showed that 24 participants would be able to detect a medium effect size ($f = 0.25$) with a coefficient of correlation of $r = 0.6$, 80% power, and $\alpha = 0.05$ using a within-between subjects design. Therefore, considering a potential drop-out rate, 30 élite judo athletes were recruited from “Banzai Cortina” Judo Club (Rome, IT). During the study, three athletes dropped out of the study because they could not ensure continuity of training. A randomised controlled interventional study was then conducted on 27 athletes (14 males and 13 females; age = 19.5 ± 2.0 years). All athletes were randomly assigned to two groups: the Fitlight-trained group (FG, n = 14; 8 males and 6 females) who, along with the traditional training, received the Fitlight training (FitT) and the control group (CG, n = 13; 6 males and 7 females) who performed only the traditional training. Sample characteristics are shown in Table 1.

The inclusion criteria to participate were:

- being in good physical and mental health and free from any conditions that might have an impact on the study;
- having completed the brown to black belt progression;
- having taken part in national or international competitive and training judo activities for at least eight years prior to the project; - demonstrating good temporal continuity in training (at least 90 min of judo training, four times a week in the last five years);
- being between 17 and 24 years old.

This study was evaluated and approved by the Institutional Review Board of eCampus University (registered number: 02/2021, 27-12-2021) in compliance with the Declaration of Helsinki and any subsequent revisions.

Prior to participating in the study, all athletes or their parents (when participants were minors) gave written and informed consent.

2.2. Fitlight

Fitlight technology is a training tool utilized in sports training all around the world. Open-skill players’ physical and visual performances can all be enhanced by its light stimuli [35]. Additionally, the light stimulus enhances their fundamental abilities and boosts their capacity to compete in a variety of sports. Additionally, it helps young players develop their physical and visual skills, which promotes responsiveness and agility and helps to form completely an athlete. The Fitlight training program is adaptable and exciting. It records a variety of human performance characteristics, including agility, speed, and reaction time. It is tablet-controlled and has eight LED-powered lights that provide real-time performance feedback. The lights may be set up for any sports or training regiment, serving as targets for the user to deactivate. In addition to being a great tool to improve open-skill abilities, this technique gives athletes and coaches access to a cutting-edge training program that improves strength, balance, and hand-eye coordination. It can also be applied to post-injury conditioning and rehabilitation [36].

2.3. Experimental procedures

The longitudinal study was conducted during the competitive phase of the season, before the World and European Championships (Guayaquil 2022 and Prague 2022) and before the beginning of any weight loss procedure. EFs were measured pre- and post-intervention (T0 and T1) and after a 2-month follow-up (T2), while physical fitness was assessed at T0 and T1. During the study period, all athletes trained 3 days per week (one session per day) for 5 weeks. Both groups performed the same volume of training but while the FG performed Fitlight training sessions, the CG was engaged in traditional judo training. After the initial warm-up phase that was common to both groups, the subsequent 25 min-phase was divided as follows:

Table 1
Sample characteristics.

	FG	CG	All participants
	(mean, SD)	(mean, SD)	(mean, SD)
Number	14	13	27
Males	8	6	14
Females	6	7	13
Age	20.1 ± 1.7	18.8 ± 2.1	19.5 ± 2.0
Weight (kg)	75.6 ± 14.6	68.5 ± 10.7	72.2 ± 13.1
Height (m)	1.7 ± 0.1	1.7 ± 0.1	1.7 ± 0.1
BMI (kg/m^2)	25.3 ± 2.5	24.3 ± 2.0	24.8 ± 2.3

FG performed FitT including uchi-komi exercises (drill of techniques without projection), for which the FitT was used to influence stimulus discrimination, inhibition ability and working memory (see Table 2). Conversely, CG performed the traditional training characterised by uchi-komi exercises (without fitlights) and technical-tactical situations aiming at technical improvement.

2.4. Measurements

2.4.1. Anthropometric measurements

Body weight, height, Body Mass Index (BMI) were assessed for all participants. Using a scale and a stadiometer, the subjects' weight and height were calculated to the nearest 0.1 kg and 0.1 cm, respectively.

2.4.2. Physical fitness assessment

2.4.2.1. Dynamic judogi chin-up. This test was used to evaluate strength endurance following the initial suggestions by Franchini et al. [37]. The athletes were instructed to perform as many accurate repetitions as they could while extending and flexing their elbows until the chin was above the hands holding the judogi (uniform used to practise judo).

The test was terminated when athletes were unable to complete the suggested execution entirely and/or stopped by themselves. During testing, they had to maintain full knee extension and were not allowed to bend their backs or lift their knees to help with the exercise. Finally, body mass was multiplied by repetitions in order to relativize the work performed by the athletes during this test. This test showed high reliability as reported by Da Silva et al. [38] with an interclass correlation coefficient of 0.98. The internal validity of this test has been assessed presenting an ICC of 0.91.

2.4.2.2. Isometric judogi chin-up. As above reported, also this test evaluated strength endurance complying with the initial suggestions by Franchini et al. [37]. The athletes were instructed to hold the position with their elbows flexed and chin elevated above the hands clutching the judogi for as long as they could. The length of time held was measured using a chronometer. The test was stopped when athletes were unable to hold the original isometric position. They held the judogi with bent elbows to begin the test. The test was terminated and the clock stopped when the athletes extended their elbows as an indication of exhaustion. In order to maintain the isometric movement for a longer period of time, athletes were expected to maintain fully extended knees and were not permitted to flex their trunks or lift their knees. Body mass was multiplied by the number of seconds in the test in order to relativize athletes' performance. Also this test showed high reliability as reported by Da Silva et al. [38] with an interclass correlation coefficient of 0.97. The internal validity of this test has been assessed presenting an ICC of 0.82.

2.4.2.3. Counter movement jump (CMJ). Lower limbs strength was evaluated by counter movement jump, using an optical detection system, consisting of a transmitting and a receiving bar (Optojump, Microgate, Udine, Italy). After a short warm-up, the athlete positioned himself between the 2 bars in an upright position with his hands on his hips. After that, he performed a quick push-up on the legs and, immediately after, a maximum vertical jump. Three trials were made with a pause of 10 s from each other and the best (highest) of the three results obtained was noted in centimetres by a specific software [39]. The Optojump system has very good validity (ICCs = 0.997–0.998) and excellent test–retest reliability (ICCs = 0.982–0.989), according to Glatthorn et al. [39].

2.4.2.4. Handgrip test. The maximum voluntary isometric grip strength of the hand was calculated with a digital dynamometer with an adjustable grip (CAMRY EH101, Senssun Weighing Apparatus Group Ltd, Guangdong, China), according to the indications of Guidetti et al. [40]. The athlete from the standing position had to hold the dynamometer with his hand. During the test, the elbow was completely extended and the arm and hand holding the dynamometer should never be in contact with the body. Without moving the arm, the athlete had to exert as much pressure as possible on the dynamometer. Two trials were made with both the right and left

Table 2
Experimental training protocol. Positive: Attack execution; negative: inhibition.

Week	Workout	Type of training	Number of fitlight colours	Notes
1st	1st	non-specific sport	1	
	2nd	uchi-komi	1	
	3rd	uchi-komi	2	1 positive colour and 1 negative
2nd	4th	non-specific sport	2	
	5th	uchi-komi	2	change colour association
	6th	uchi-komi	2	change colour association
3rd	7th	non-specific sport	3	2 positive colours and 1 negative
	8th	uchi-komi	3	
	9th	uchi-komi	3	change colour association
4th	10th	uchi-komi	3	change colour association
	11th	uchi-komi	4	2 positive colours and 2 negative
	12th	uchi-komi	4	change colour association
5th	13th	uchi-komi	4	change colour association
	14th	uchi-komi	4	change colour association
	15th	uchi-komi	4	change colour association

hands, with a short break from each other and the best of the two results obtained is noted in kilograms. Isometric Handgrip Strength test measured with grip dynamometer showed high reliability ($R = 0.96$) as reported by Guidetti et al. [40]. The internal validity of this test has been assessed presenting an ICC of 0.94 for the dominant hand.

2.4.3. BDNF measurements

BDNF was analysed by saliva analysis. Ultrapure polypropylene sampling devices (SaliCaps) with an absorption of less than 5% were used. Athletes were advised not to eat, drink or chew gum 30 min before taking a saliva sample as it could interfere with the results. Saliva samples with any blood contamination due to bleeding gums or wounds in the oral cavity were discarded [41]. In order to minimise viscosity and make the solution easier to pipette and aliquot as needed, samples were subjected to a freeze and thaw cycle prior to analysis [42]. Saliva samples were taken before and after the first experimental training on both groups and before and after the last experimental training.

2.4.4. EFs assessment

2.4.4.1. Flanker/Reverse Flanker task. The Flanker/Reverse Flanker task was performed using a computer [43,44]. A set of five fish (blue or pink) were displayed in each of the three successive blocks that composed this test. In the first block all fish were blue and athletes had to point in the correct direction of the central fish, responding selectively and ignoring lateral stimuli. Athletes were asked to press key "L" if the central fish was facing right and key "A" if the central fish was facing left. In the second block (Reverse Flanker), where pink fish were showed, the athletes had to push the button corresponding to the external fish, ignoring the other ones. The blue and pink fish were alternated at random in block 3, while adhering to the fish's colour criteria. Thus, the test required attention control, inhibiting overbearing responses, reorienting where to focus one's attention, and remembering both rules [1,43,45]. Then, the test evaluated fundamental EFs (working memory, inhibitory control, and cognitive flexibility). In the first two blocks, the athletes completed 22 trials (16 congruent and 6 incongruent), and in the third block, they completed 44 trials (32 congruent and 12 incongruent), for a total of 88 trials. The athletes got visual feedback during the practice trials that preceded each block (4 trials for first and second blocks and 8 trials for third block). These practice trials were not included in the analysis. The percentage of correct answers (accuracy) and the mean value of choice-reaction time (RT) on correct ones were calculated. The Flanker test showed good reliability ($ICC = 0.805–0.874$) as reported by Hooper et al. [44]. The internal validity of this test has been assessed presenting an ICC that is between 0.88 and 0.94.

2.4.4.2. Digit span task. The Forward-Digit Span and the Backward-Digit Span tasks made up the Digit Span task employed in this study. Short-term memory was tested in the first one and working memory was tested in the second one [1]. The athletes had to enter a set of digits on a computer keyboard in a certain order after reading them on a screen at a pace of one digit per second. They received a longer list if they wrote the numbers in the right sequence. The number of digits increased by one until the athlete failed consecutively two attempts of the same digit span length. The digit span was represented by the length of the longest list an athlete could remember. Athletes in the Forward-Digit Span were instructed to repeat back the items in the same order they had read. On the other hand, athletes in the Backward-Digit Span had to write the digits backwards [46]. The highest number of digits successfully obtained was the span score. Moreover, it has been calculated the rate of correct score (RCS), which is equal to the number of correct answers divided by the average response time (RT in ms). The Forward-Digit Span and the Backward-Digit Span tasks showed a reliability of 0.89 and 0.59, respectively, as reported by De Paula et al. [47]. The internal validity of this test has been assessed presenting an ICC that is between 0.83 and 0.91.

2.5. Statistical analysis

Data were initially screened for outliers and normal distribution. Logarithmic transformation was applied when the assumption of normality was violated. To examine the intervention's effects on cognitive measures (i.e., Flanker, Digit-Span), a series of 2x3 repeated measures analysis of variance (RM-ANOVA) were performed with Group (2 levels: Experimental, Control) was the between-subject factor, and Time (3 levels: T0, T1, T2) as within-subject factors. Moreover, potential intervention's effects on fitness measures (i.e., handgrip, CMJ, absolute and relative DC, absolute and relative IC) were examined with a series of 2x2 RM-ANOVA with Group (2 levels: Experimental, Control) as the between-subject factor, and Time (2 levels: T0, T1) as the within-subject factor. Additionally, two different $2 \times 2 \times 2$ RM-ANOVA were performed to examine the effects of the intervention on salivary measures (i.e., BDNF), with Group (2 levels: Experimental, Control) as the between-subject factor, and Time (2 levels: T0, T1) and Session (2 levels: pre-session, post-session) as within-subject factors. Also, athletes' competitive results within 3 months after the end of the intervention was calculated by Chi^2 test: specifically, all the national and international competition matches (won vs lost) were considered across this period. Sphericity of data was tested via Mauchly's test, and Greenhouse-Geisser correction was applied whenever the assumption was violated. Effect sizes for significant interaction effects are reported as partial eta squared ($\eta^2 p$), with 0.01, 0.06, and 0.14 reflecting small, medium, and large effects, respectively [48,49]. Critical α was set at $p \leq 0.05$ for significance level, and all post hoc analyses were Tukey Honestly Significant Difference (HSD) corrected. Analyses were performed on Jamovi (v. 2.3; The Jamovi Project, 2022) for Windows and R-Studio for R (v. 4.3).

3. Results

3.1. Executive functions

3.1.1. Flanker/Reverse Flanker task

The mixed model ANOVA with Greenhouse-Geisser correction indicated a significant interaction (Time x Group) for Flanker accuracy performance, F (1.44, 36.05) = 7.62, $p = 0.004$, $\eta^2 p = 0.234$. Post hoc analyses revealed that the accuracy of the experimental group differed significantly from the control group at T1 (98.30 % vs 92.05 %, $p = 0.028$), with the experimental group being more accurate than the controls (Fig. 1). Also, the control group was less accurate at T1 than the experimental group at T2 (97.73 %, $p = 0.035$). In terms of reaction times, no significant difference was detected ($p = 0.280$).

3.1.2. Forward- and backward-digit span

In the forward version of the Digit Span, the RM-ANOVA with Greenhouse-Geisser correction indicated a significant interaction (Time x Group) for the Rate of Correct Score, F (1.42, 35.42) = 8.588, $p = 0.003$, $\eta^2 p = 0.256$. After Tukey HSD correction, post hoc analyses indicated no significant difference between the two groups as measured at different time points. Furthermore, no significant interaction effects were detected neither for Span ($p = 0.157$) nor for RTs ($p = 0.352$). In the backward version, the RM-ANOVA revealed a significant interaction (Time x Group) for the Span, F (2, 50) = 4.147, $p = 0.021$, $\eta^2 p = 0.143$. Post hoc analyses showed a significant difference in the experimental group (Fig. 2) between T0 and T2 (3.571 vs 5.214, $p < 0.001$). No significant interaction effects were detected for RCS ($p = 0.088$) nor for RTs ($p = 0.905$).

3.2. Fitness test

Table 3 and Table 4 show results of motor and cognitive tests.

3.2.1. Dynamic chin-up

In terms of absolute values, the RM-ANOVA revealed a significant interaction (Time x Group), F (1,25) = 7.070, $p = 0.013$, $\eta^2 p = 0.220$. After Tukey HSD correction, post hoc analyses indicated no significant difference between the two groups at different measurement time points. Similarly to its absolute values, the RM-ANOVA performed on the relative values of the dynamic chin-up showed a significant interaction (Time x Group), F (1,25) = 8.280, $p = 0.008$, $\eta^2 p = 0.249$. Post hoc analyses revealed that participants in the experimental group significantly improved their performance (Fig. 3) from T0 (M = 11.50) than at T1 (M = 14.29) ($p = 0.027$).

3.2.2. Isometric chin-up

In terms of absolute values, the RM-ANOVA revealed a significant interaction (Time x Group), F (1,25) = 7.820, $p = 0.010$, $\eta^2 p = 0.238$. Tukey HSD corrected post hoc analyses indicated no significant difference between the two groups. The RM-ANOVA performed on the relative values of the isometric chin-up revealed a significant interaction (Time x Group), F (1,25) = 7.794, $p = 0.010$, $\eta^2 p = 0.238$. Tukey HSD corrected post hoc analyses indicated no significant difference between the two groups at different measurement time points.

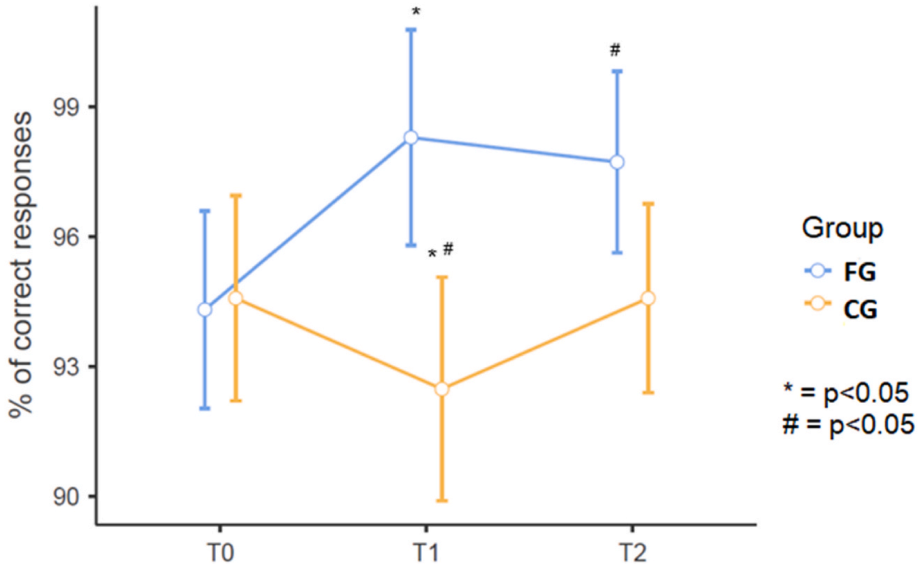

Fig. 1. Flanker accuracy.

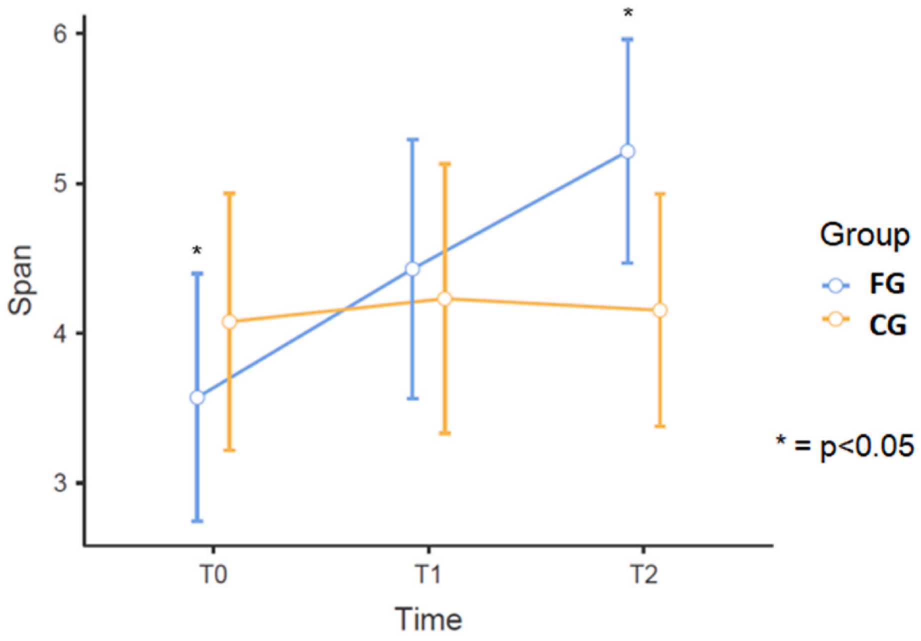

Fig. 2. Span in backward digit span.

Table 3
Results of motor tests (mean values and standard deviation).

Variables	Pre				Post			
	FG		CG		FG		CG	
CMJ (cm)	29,2	7,9	32,4	7,6	31,5	8,0	30,6	7,6
DC_abs (rep)	11,5	7,8	10,6	8,5	14,3	9,3	9,4	7,0
DC_rel (rep*kg)	834,5	560,6	737,0	609,6	1055,9	656,8	654,8	501,6
IC_abs (s)	42,5	19,0	41,9	17,4	47,9	20,3	34,1	16,2
IC_rel (s*kg)	3104,3	1282,4	2836,5	1133,9	3522,7	1359,7	2379,9	1265,5
HG_dx (kg)	42,9	12,2	40,3	9,6	46,5	12,2	43,0	11,7
HG_sx (kg)	41,6	9,6	39,2	10,0	44,3	10,0	41,4	11,5

Table 4
Results of cognitive tests (mean values and standard deviation).

Variables	Pre				Post				Follow-up			
	FG		CG		FG		CG		FG		CG	
Flanker accuracy (%)	94,3	5,2	94,6	2,6	98,3	1,7	92,5	6,3	97,7	2,1	94,6	5,1
Flanker RT (ms)	656,7	69,8	651,6	89,0	627,1	71,6	662,5	81,0	613,0	52,7	636,9	84,1
Digit foreward span	4,9	1,2	4,7	0,8	5,6	1,0	4,9	1,1	5,6	1,0	4,7	0,9
Digit foreward RT (ms)	2267,3	460,7	2100,3	457,2	2359,0	357,3	2408,9	408,6	2396,8	425,8	2256,2	392,5
Digit foreward RCS	3,6	0,9	4,3	1,1	4,3	0,8	4,0	1,1	4,4	0,7	3,6	1,2
Digit backward span	3,6	1,4	4,1	1,6	4,4	1,2	4,2	1,9	5,2	0,8	4,2	1,8
Digit backward RT (ms)	3025,5	1579,1	3104,9	1538,7	3541,0	1398,7	3731,4	1666,6	3605,9	957,7	3550,2	935,3
Digit backward RCS	2,1	0,7	2,4	0,7	2,5	1,2	2,1	0,8	2,6	0,9	2,1	0,8

3.2.3. *Counter movement jump*

The RM-ANOVA revealed a significant interaction (Time x Group), F (1,25) = 11.520, p = 0.002, $\eta^2 p = 0.315$. Tukey HSD corrected post hoc analyses revealed that participants in the experimental group significantly improved their performance (Fig. 4) from T0 (M = 29.21) than at T1 (M = 31.49) (p = 0.05).

3.2.4. *Handgrip test*

No significant interaction effect was detected for the measure of HG ($p > 0.05$).

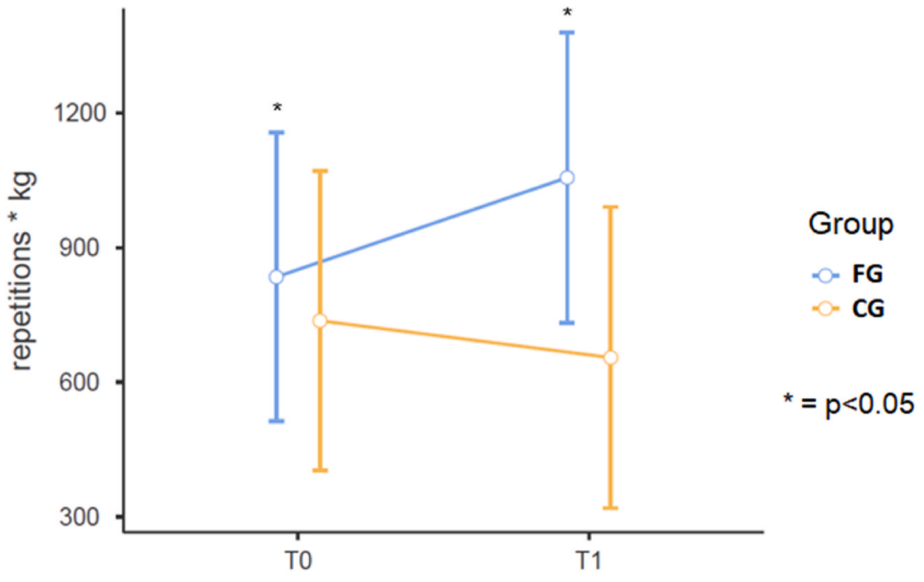

Fig. 3. Dynamic chin up.

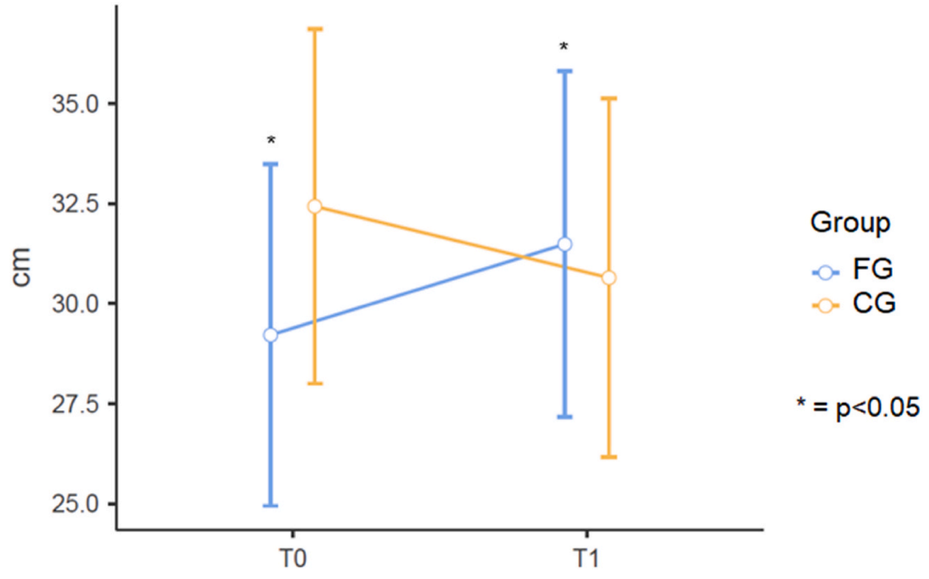

Fig. 4. CMJ

3.3. BDNF analysis

The RM-ANOVA on BDNF measures did not reveal any significant interaction (all, $p > 0.05$).

3.4. Competitive results

The FG won 64.3% of competitive matches after the training period compared to 38.5% won by the CG ($\chi^2 = 1.187$; $p < 0.01$; $\varphi = 0.257$).

4. Discussion

The current study examined the impact of CMT on cognitive and physical variables in élite judo athletes after a period of mass training. Our hypothesis was that a CMT with Fitlight™ would show an improvement in EFs and a tendency to increase in the physical fitness and BDNF levels in the experimental group compared to the non-intervention group. Moreover, for FG athletes, a better results in competitions were expected.

The main finding of this study was that five weeks of massed judo training improved the accuracy of answers for the flanker test and the span in the backward-digit span of athletes of the FG which represents a measure of working memory. Moreover, results showed that this effect was maintained also 8 weeks after the end of the CMT.

These results are in line with our initial hypothesis. Moreover, the Fitlight-trained group showed improvements over time (from T0 to T2) for the rate of correct score of forward digit span, which is an index of working memory processing speed. Therefore, these results indicate that a Fitlight intervention along with traditional judo training could enhance working memory as previously reported [1]. However, no other significant differences between the groups for the other EFs tasks were found. These results could be explained by two reasons: 1) as élite athletes, they already had high levels of EFs, as it was verified at T0, 2) as athletes were tested in a competitive period, the CMT could not last longer than 25 min which is, anyway, a similar amount of training reported by previous studies [33,50].

However, as no differences in reaction times between the groups were found, these findings need to be interpreted with caution. Indeed, Badau and colleagues [33], who used Fitlight™ technology in open-skill sports training with adolescents athletes, reported that cognitive reaction time, a parameter used to measure cognitive flexibility, had improved after a 3-month intervention. In addition, they found that open-skill sports athletes who underwent CMT experienced notable gains in cognitive testing and athletic ability. Then, the different intervention duration could be the cause of the disparate results: in our study, the intervention lasted 5 weeks and involved three times a week of mass Fitlight training, whereas Badau and colleagues [33] employed a distributed 12-week program. Despite having a similar overall training load, distributed cognitive training may be a prerequisite for achieving appreciable EFs increases during sports practice. Because of this, our 5-week program was unable to produce significant cognitive improvements, with the exception of the accuracy of answers in the flanker test and the span in the backward-digit span.

Therefore, more research is required to determine the possible advantages of Fitlight training for EFs in élite athletes practising open-skill sports. Specifically, in order to understand the ideal volume and frequency for cognitive improvement, it may be pertinent to examine different distributions of cognitive training (massed vs distributive).

Regarding physical fitness, after the 5-week massed training, there was a significant improvement in dynamic chin-up and in CMJ and a considerable improvement in isometric chin-up scores. However, for the latter, there was no significant difference between the groups. These findings could be mostly attributed to the intervention's focus on improving cognitive skills rather than physical fitness. Furthermore, as élite athletes, the participants already started from a higher level of fitness performances.

Moreover, this study examined the effect of traditional judo training and Fitlight training on BDNF saliva levels in élite judo athletes. A growing number of studies have looked at BDNF levels during short-term and long-term exercise both in healthy individuals and in individuals with chronic conditions [51,52]. Results showed that increased blood BDNF may therefore be influenced by both the degree of PA and the training status. In our study no significant differences were found in BDNF levels, probably because of the intervention duration. In addition, BDNF collection was made by saliva rather than blood sampling.

Regarding the competitive results obtained by FG athletes after the end of the intervention, it was observed a significant difference between FG and CG in terms of won matches (64.3% vs 38.5%). This result is meaningful as all subjects were élite athletes, therefore even if more studies are needed, it seems that CMT with Fitlight™ could be considered an additional support to coaches during the training period.

This study has several strengths: 1) First of all it is the first study using Fitlight™ in judo. In particular, the sport-specific training sessions were carried out in real conditions, proper open skill sports, part of the daily routine for élite athletes. 2) In our study only élite athletes were recruited, both in the experimental and control groups. In fact, the athletes in our study trained for about 20 h per week and had taken part in national/international competitions, which was rarely the case in earlier studies.

This research also has some limitations. Indeed, it is reasonable that the duration of the intervention, though massive, was likely short to induce any potential variations in EFs improvement in response to CMT. According to the available research, 8–12 weeks of CMT can provide improvements in EFs [33,53] and a distributed schedule appears to be a prerequisite for EFs development in open-skill sports. However, as above mentioned, a 5-week intervention was due to athletes' seasonal sporting duties. Furthermore, although validated physical and cognitive tests were employed in the study, it is uneasy to design ecological protocols aimed at analysing the improvement in EFs during match actions, without interfering with the context [50].

Moreover, BDNF collection was made by saliva sampling, a non-invasive alternative and simple to use method, compared to blood sampling, which is most reliable but invasive and uneasy to be carried out in on-court condition. Unfortunately, BDNF could not be considered reliable in saliva as it is in blood sampling. Indeed, commercial BDNF kits may not be ready for non-invasive saliva measurements, which limits the sampling frequency and settings [54,55].

5. Conclusions

A 5-week specific judo CMT using the Fitlight training method enhanced élite judo athletes' cognitive ability, namely the cognitive flexibility accuracy and the working memory, and physical performance, specifically strength endurance. A CMT lasting only 5 weeks seems to be able to further enhance some EFs tasks in élite judo athletes and also some components of physical fitness. This information may be considered by coaches when creating seasonal training plans. The connections between EFs and motor training still raise many unanswered research questions. Future studies should investigate which EFs are improved by a particular CMT to better understand the potential effects of higher EFs on various sports, possibly with a motor task to better trigger EFs activation, as well as the duration of these improvements.

Data availability statement

The dataset will be made available upon reasonable request to the corresponding author.

CRediT authorship contribution statement

M. Campanella: Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **L. Cardinali:** Writing – original draft, Methodology, Data curation, Conceptualization. **D. Ferrari:** Visualization, Data curation. **S. Migliaccio:** Resources, Funding acquisition, Data curation. **F. Silvestri:** Data curation. **L. Falcioni:** Data curation. **V. Bimonte:** Data curation. **D. Curzi:** Writing – review & editing, Methodology, Data curation. **M. Bertollo:** Methodology, Formal analysis, Data curation. **L. Bovolon:** Formal analysis. **M.C. Gallotta:** Visualization, Methodology. **L. Guidetti:** Supervision, Methodology, Formal analysis. **C. Baldari:** Writing – review & editing, Supervision, Methodology, Conceptualization. **V. Bonavolontà:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Although I am serving as associate editor for Heliyon I do not have any access to the reviewing process (Maurizio Bertollo) If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

A special thanks to the owners, coaches and athletes of Banzai Cortina of Rome, for their willingness and kindness.

References

[1] A. Diamond, Executive functions, Annu. Rev. Psychol. 64 (2013) 135–168.
[2] B. Luna, Developmental changes in cognitive control through adolescence, Adv. Child Dev. Behav. 37 (2009) 233–278.
[3] A. Diamond, Evidence of robust recognition memory early in life even when assessed by reaching behavior, J. Exp. Child Psychol. 59 (3) (1995) 419–456.
[4] E.A. Crone, C. Wendelken, S. Donohue, L. van Leijenhorst, S.A. Bunge, Neurocognitive development of the ability to manipulate information in working memory, Proc. Natl. Acad. Sci. USA 103 (24) (2006) 9315–9320.
[5] M.C. Davidson, D. Amso, L.C. Anderson, A. Diamond, Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching, Neuropsychologia 44 (11) (2006) 2037–2078.
[6] N.J. Cepeda, A.F. Kramer, J. Gonzalez de Sather, Changes in executive control across the life span: examination of task-switching performance, Dev. Psychol. 37 (5) (2001) 715.
[7] A. Diamond, Activities and programs that improve children's executive functions, Curr. Dir. Psychol. Sci. 21 (5) (2012) 335–341.
[8] A. Kolovelonis, M. Goudas, Acute enhancement of executive functions through cognitively challenging physical activity games in elementary physical education, Eur. Phys. Educ. Rev. 29 (2) (2023) 268–285.
[9] F. Contreras-Osorio, I.P. Guzmán-Guzmán, E. Cerda-Vega, L. Chirosa-Ríos, R. Ramírez-Campillo, C. Campos-Jara, Effects of the type of sports practice on the executive functions of schoolchildren, Int. J. Environ. Res. Publ. Health 19 (7) (2022) 3886.
[10] F. Contreras-Osorio, C. Campos-Jara, C. Martínez-Salazar, L. Chirosa-Ríos, D. Martínez-García, Effects of sport-based interventions on children's executive function: a systematic review and meta-analysis, Brain Sci. 11 (6) (2021) 755.
[11] A.F. Beavan, J. Spielmann, J. Mayer, S. Skorski, T. Meyer, J. Fransen, Age-related differences in executive functions within high-level youth soccer players, Brazil. J. Motor Behav. 13 (2) (2019) 64–75.
[12] D.T. Stuss, Biological and psychological development of executive functions, Brain Cognit. 20 (1) (1992) 8–23.
[13] F. Heilmann, D. Memmert, H. Weinberg, F. Lautenbach, The relationship between executive functions and sports experience, relative age effect, as well as physical maturity in youth soccer players of different ages, Int. J. Sport Exerc. Psychol. 21 (2) (2023) 271–289.
[14] C.H. Wang, C.C. Chang, Y.M. Liang, C.M. Shih, W.S. Chiu, P. Tseng, C.H. Juan, Open vs. closed skill sports and the modulation of inhibitory control, PLoS One 8 (2) (2013) e55773.
[15] F. Heilmann, H. Weinberg, R. Wollny, The impact of practicing open-vs. closed-skill sports on executive functions—a meta-analytic and systematic review with a focus on characteristics of sports, Brain Sci. 12 (8) (2022) 1071.
[16] Q. Gu, L. Zou, P.D. Loprinzi, M. Quan, T. Huang, Effects of open versus closed skill exercise on cognitive function: a systematic review, Front. Psychol. 10 (2019) 1707.
[17] A. Diamond, Effects of physical exercise on executive functions: going beyond simply moving to moving with thought, Annals of sports medicine and research 2 (1) (2015) 1011.
[18] D. Formenti, A. Trecroci, M. Duca, L. Cavaggioni, F. D'Angelo, A. Passi, G. Alberti, Differences in inhibitory control and motor fitness in children practicing open and closed skill sports, Sci. Rep. 11 (1) (2021) 4033.
[19] T. Vestberg, G. Reinebo, L. Maurex, M. Ingvar, P. Petrovic, Core executive functions are associated with success in young elite soccer players, PLoS One 12 (2) (2017) e0170845.
[20] B.C. Huijgen, S. Leemhuis, N.M. Kok, L. Verburgh, J. Oosterlaan, M.T. Elferink-Gemser, C. Visscher, Cognitive functions in elite and sub-elite youth soccer players aged 13 to 17 years, PLoS One 10 (12) (2015) e0144580.
[21] F. Policastro, A. Accardo, R. Marcovich, G. Pelamatti, S. Zoia, Relation between motor and cognitive skills in Italian basketball players aged between 7 and 10 years old, Sports 6 (3) (2018) 80.
[22] A. Amato, V. Giustino, A. Patti, P. Proia, T. Trivic, P. Drid, A. Bianco, Young basketball players have better manual dexterity performance than sportsmen and non-sportsmen of the same age: a cross-sectional study, Sci. Rep. 13 (1) (2023) 20953.
[23] H. Alves, M.W. Voss, W.R. Boot, A. Deslandes, V. Cossich, J.I. Salles, A.F. Kramer, Perceptual-cognitive expertise in elite volleyball players, Front. Psychol. 4 (2013) 36.
[24] T. Ishihara, S. Sugasawa, Y. Matsuda, M. Mizuno, Improved executive functions in 6–12-year-old children following cognitively engaging tennis lessons, J. Sports Sci. 35 (20) (2017) 2014–2020.
[25] K.D. Lakes, W.T. Hoyt, Promoting self-regulation through school-based martial arts training, J. Appl. Dev. Psychol. 25 (3) (2004) 283–302.
[26] W.L.A. Lo, Z. Liang, W. Li, S. Luo, Z. Zou, S. Chen, Q. Yu, The effect of judo training on set-shifting in school children, BioMed Res. Int. 2019 (2019).
[27] M. Alesi, A. Bianco, J. Padulo, F.P. Vella, M. Petrucci, A. Paoli, A. Pepi, Motor and cognitive development: the role of karate, Muscles, ligaments and tendons journal 4 (2) (2014) 114.
[28] K.D. Lakes, T. Bryars, S. Sirisinahal, N. Salim, S. Arastoo, N. Emmerson, C.J. Kang, The healthy for life taekwondo pilot study: a preliminary evaluation of effects on executive function and BMI, feasibility, and acceptability, Mental health and physical activity 6 (3) (2013) 181–188.

[29] Q. Yu, C.C. Chan, B. Chau, A.S. Fu, Motor skill experience modulates executive control for task switching, Acta Psychol. 180 (2017) 88–97.

[30] S.Y. Cho, W.Y. So, H.T. Roh, The effects of taekwondo training on peripheral neuroplasticity-related growth factors, cerebral blood flow velocity, and cognitive functions in healthy children: a randomized controlled trial, Int. J. Environ. Res. Publ. Health 14 (5) (2017) 454.

[31] M.W. Voss, R.S. Prakash, K.I. Erickson, C. Basak, L. Chaddock, J.S. Kim, A.F. Kramer, Plasticity of brain networks in a randomized intervention trial of exercise training in older adults, Front. Aging Neurosci. 2 (2010) 32.

[32] S. Lucia, V. Bianco, L. Boccacci, F. Di Russo, Effects of a cognitive-motor training on anticipatory brain functions and sport performance in semi-elite basketball players, Brain Sci. 12 (1) (2021) 68.

[33] D. Badau, A. Badau, C. Ene-Voiculescu, A. Larion, V. Ene-Voiculescu, I. Mihaila, A. Abramiuc, The impact of implementing an exergame program on the level of reaction time optimization in Handball, volleyball, and basketball players, Int. J. Environ. Res. Publ. Health 19 (9) (2022) 5598.

[34] Fitlight system, Available online: https://www.fitlighttraining.com/products/fitlight-system. (Accessed 12 October 2022).

[35] A.K. Hassan, M.M. Alhumaid, B.E. Hamad, The effect of using reactive agility exercises with the FITLIGHT training system on the speed of visual reaction time and dribbling skill of basketball players, Sports 10 (11) (2022) 176.

[36] A.K. Hassan, M.S. Alibrahim, Y.A.R. Sayed Ahmed, The effect of small-sided games using the FIT LIGHT training system on some harmonic abilities and some basic skills of basketball players, Frontiers in Sports and Active Living 5 (2023) 3.

[37] E. Franchini, B. Miarka, L. Matheus, F.B. Del Vecchio, Endurance in judogi grip strength tests: comparison between elite and non-elite judo players, Archives of Budo 7 (1) (2011) 1–4.

[38] B.V.C.D. Silva, M. Marocolo Junior, M.A.D.M. Simim, F.N. Rezende, E. Franchini, G.R.D. Mota, Reliability in kimono grip strength tests and comparison between elite and non-elite Brazilian Jiu-Jitsu players, Archives of Budo 8 (2) (2012) 103–107.

[39] J.F. Glatthorn, S. Gouge, S. Nussbaumer, S. Stauffacher, F.M. Impellizzeri, N.A. Maffiuletti, Validity and reliability of Optojump photoelectric cells for estimating vertical jump height, J. Strength Condit Res. 25 (2) (2011) 556–560.

[40] L. Guidetti, A. Musulin, C. Baldari, Physiological factors in middleweight boxing performance, J. Sports Med. Phys. Fit. 42 (3) (2002) 309–314.

[41] K.T. Kivlighan, D.A. Granger, E.B. Schwartz, V. Nelson, M. Curran, E.A. Shirtcliff, Quantifying blood leakage into the oral mucosa and its effects on the measurement of cortisol, dehydroepiandrosterone, and testosterone in saliva, Horm. Behav. 46 (1) (2004) 39–46.

[42] O.C. Schultheiss, S.J. Stanton, Assessment of salivary hormones, Methods in social neuroscience 17 (2009).

[43] A. Diamond, W.S. Barnett, J. Thomas, S. Munro, Preschool program improves cognitive control, Science 318 (5855) (2007) 1387–1388.

[44] B. Hooper, L.O. Faria, L.D.S. Fortes, S.P. Wanner, M.R. Albuquerque, Development and reliability of a test for assessing executive functions during exercise, Appl. Neuropsychol.: Adult 29 (4) (2022) 750–760.

[45] J. Hogan, S. Cordes, S. Holochwost, E. Ryu, A. Diamond, E. Winner, Is more time in general music class associated with stronger extra-musical outcomes in kindergarten? Early Child. Res. Q. 45 (2018) 238–248.

[46] R.D. Samuel, O. Zavdy, M. Levav, R. Reuveny, U. Katz, G. Dubnov-Raz, The effects of maximal intensity exercise on cognitive performance in children, J. Hum. Kinet. 57 (2017) 85.

[47] J.J. de Paula, L.F. Malloy-Diniz, M.A. Romano-Silva, Reliability of working memory assessment in neurocognitive disorders: a study of the Digit Span and Corsi Block-Tapping tasks, Brazilian Journal of Psychiatry 38 (2016) 262–263.

[48] D. Lakens, Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs, Front. Psychol. 4 (2013) 863.

[49] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, Academic press, 2013.

[50] F. Silvestri, M. Campanella, M. Bertollo, M.R. Albuquerque, V. Bonavolontà, F. Perroni, D. Curzi, Acute effects of fitlight training on cognitive-motor processes in young basketball players, Int. J. Environ. Res. Publ. Health 20 (1) (2023) 817.

[51] T. Seifert, P. Brassard, M. Wissenberg, P. Rasmussen, P. Nordby, B. Stallknecht, N.H. Secher, Endurance training enhances BDNF release from the human brain, Am. J. Physiol. Regul. Integr. Comp. Physiol. 298 (2) (2010) R372–R377.

[52] S.R. Vega, H.K. Strüder, B.V. Wahrmann, A. Schmidt, W. Bloch, W. Hollmann, Acute BDNF and cortisol response to low intensity exercise and following ramp incremental exercise to exhaustion in humans, Brain Res. 1121 (1) (2006) 59–65.

[53] V. Benzing, M. Schmidt, The effect of exergaming on executive functions in children with ADHD: a randomized clinical trial, Scand. J. Med. Sci. Sports 29 (8) (2019) 1243–1253.

[54] C. Vrijen, H.M. Schenk, C.A. Hartman, A.J. Oldehinkel, Measuring BDNF in saliva using commercial ELISA: results from a small pilot study, Psychiatr. Res. 254 (2017) 340–346.

[55] A.L. Mandel, H. Ozdener, V. Utermohlen, Brain-derived neurotrophic factor in human saliva: ELISA optimization and biological correlates, J. Immunoassay Immunochem. 32 (1) (2011) 18–30.